

FINAL REPORT

DEVELOPMENT OF A NON-MAGNETIC
FLIGHT TYPE MASS SPECTROMETER

by

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CONTRACT NAS8-21217

for

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ABSTRACT

This program has resulted in the design, construction and test of a small ruggedized flight feasibility model of a mass spectrometer, based on the monopole principle, and intended for ultimate use in Saturn space vehicles. This report describes in detail the equipment, gives the operating principles, discusses the tests made, considers applications and makes recommendations for future activities.

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I. INTRODUCTION

The Non-Magnetic Flight Type Mass Spectrometer is a development model of a small, light weight, low power consumption, high resolution and sensitive mass spectrometer to be used during space vehicle flights. The development model mass spectrometer and electronics have been designed to meet severe vibration specifications but otherwise meet only normal laboratory environmental specifications. The Ion Pump has not been ruggedized, and must be removed during vibration tests.

The unit was originally conceived as a device for monitoring the presence of hydrogen and other propellant fuels and oxidizers in the interstage regions of the SATURN IB and SATURN V, and in the passivated S-IV-B workshop region. A study of these applications was conducted as part of this program. The results of the study are included in this report. The unit could also be used as a caution monitor in the pressurized S-IV-B workshop. This application was considered briefly in the study.

The major portion of the program consisted of the ruggedization and weight reduction of the mass spectrometer tube; the design of light weight, low power consumption solid state electronics; and the design of a suitable package including vibration isolators. The tube ruggedization program was based on a redesign of a General Electric commercial mass spectrometer tube known as the Monopole 600 Partial Pressure Analyzer. The electronics design was based on the electronics used with this commercial tube. The commercial design employed many electron tubes, and did not seek to minimize power consumption.

In this report the theory of operation and general description of the mass spectrometer are given, followed by discussions of the development and design of the tube, the electronics, and the packaging. Also given is a description of the tests to which the overall equipment was subjected and the results of these tests. Recommendations and conclusions, based on the results of these tests, are also given.

This program was a joint effort of the Apollo Systems Department and the Vacuum Products Business Section* of the General Electric Company. The Apollo Systems Department assumed the responsibility for the overall program, the electronics, the packaging and final assembly and test. The Vacuum Products Business Section furnished the mass spectrometer, the ion pump, the vacuum plumbing, and information on the electronics used in the commercial version.

Within the Apollo Systems Department the program was led by Larry Shaffer, with the electronics being the responsibility of Shannon Little, and the packaging the responsibility of Waybern Wakefield. At the Vacuum Products Business Section, John Hedman was responsible for all effort.

* The name of this component has been recently changed to the Analytical Measurements Business Section.

II. GENERAL DESCRIPTION

One of the major problems associated with liquid or cryogenic fuels used in space vehicles is the detection of leaks. Where the leaks result in the presence of hazardous gases, which can result in fires or explosions, there is great need to measure the total and partial pressures of the various constituents in the vehicle atmosphere. In the Saturn launch vehicles the problem has been solved to date, before launch, by the use of sampling tubes running to many locations from a modified commercial mass spectrometer located near the base of the vehicle. These tubes are inconvenient, and cause a time delay in detection.

To monitor these gases after launch and to add additional capabilities, the Astrionics Laboratory of the George C. Marshall Space Flight Center, National Aeronautics and Space Administration, has been seeking a small, lightweight, reliable mass spectrometer which could be located in space vehicles. In addition to monitoring functions during launch and flight periods, this equipment could also be used to monitor preflight operations. As well as monitoring a single substance, as in leak detection, this equipment can also be used to sample a wide range of constituents as needed in environmental and contamination analysis. This type of analysis is particularly desired in the vicinity of some experimental payloads. In addition, the spectrometer can be used for atmospheric research both in earth orbit and deep space planetary probes.

This program included an applications study in order to determine further the detailed requirements of the mass spectrometer, particularly that of mass range. Another requirement was the development, design, construction and delivery of a breadboard model. The specifications of this model as stated in the Scope of Work of the contract, are:

1. General

The applications can be divided into three groups according to mass range as follows:

- (a) Detection of hydrogen, oxygen, and hazardous gas mixtures. Also general gas monitoring, such as carbon dioxide, water vapor, and the lighter atmospheric constituents. Mass range 2-50 AMU.
- (b) Measurement of ambient atmospheric constituents, hydro-carbon fuels, toxic gases, combustion products, constituents due to outgassing, etc. Mass range 2-300 AMU.
- (c) Detection of heavier hydro-carbon contaminants and toxic gases. Mass range 1-600 AMU.

While this effort will concentrate primarily on the masses below 300 AMU the basic mass analyzer should be capable of separating masses up to 600. The study should describe the modifications and design changes necessary to extend the mass range.

In order to make measurements at pressures higher than that of which the ionization source and analyzer will operate, the unit must include a sampling orifice and a pumping system.

The mass spectrometer shall be rugged, insensitive to shock and vibration, small in size and weight, and require low operating power. It shall be constructed to good air-borne standards of materials compatible to the operating media. The spectrometer shall have a high reliability and long life. It must be capable of bakeout at temperatures up to 250°C.

2. Environment

The spectrometer shall be shown to be inherently capable of withstanding and operating under the conditions of radiation, atmospheric environment, vibration and shock, and acoustic environment that might normally be encountered in the applications discussed, including operation from atmospheric pressure to 10^{-10} torr. The spectrometer to be delivered is a feasibility model as opposed to flight hardware. The spectrometer tube and associated components will, however, be ruggedized with the goal of operating during vibration conditions defined as $0.6G^2/Hz$ random vibration from 20-2000 Hz when mounted on suitable vibration isolation mounting.

3. Performance

This effort will be guided by the following performance specifications:

Sensitivity	Partial pressure measurement to 10^{-10} torr
Resolution	Unit resolution over mass range (10% valley between adjacent peaks)
Scan Rate	60 seconds over entire range and manual scan
Mass Range	1-300 AMU (See paragraph 1B1).
Readout	Output suitable for driving a recorder (0-5V)
Power	Not more than 30 watts
Weight	16.8 pounds
Size	6" x 8" x 16"

4. Quality and Reliability

Since this is primarily a study and development effort, quality and reliability requirements are not applicable. Flight units, however, would be required to meet applicable standards and procedures such as NPC 200-3, NPC 200-4, and MSFC-STD-154, and therefore, as part of the demonstration of feasibility it should be shown that these requirements can be met.

In fulfillment of the contract, the applications study was performed. A summary of its major findings and conclusions is included as Appendix A of this report.

This report is primarily concerned with the breadboard equipment which was delivered. This equipment is basically a redesign for weight, size, and power reductions and ruggedization of a standard monopole type commercial mass spectrometer manufactured by the Vacuum Products Business Section of the General Electric Company located in Schenectady, New York.

The description of the overall instrument which follows will touch only briefly on the operating principles. A more detailed description is given in Appendix B.

Referring to Figure 1, the spectrometer operates by sampling a gas through a small leak, the size of which is a function of the ambient pressure surrounding the equipment. When the equipment is to be used over a wide range of ambient pressures, the leak size must be varied to be small for high pressures and large for low pressures.

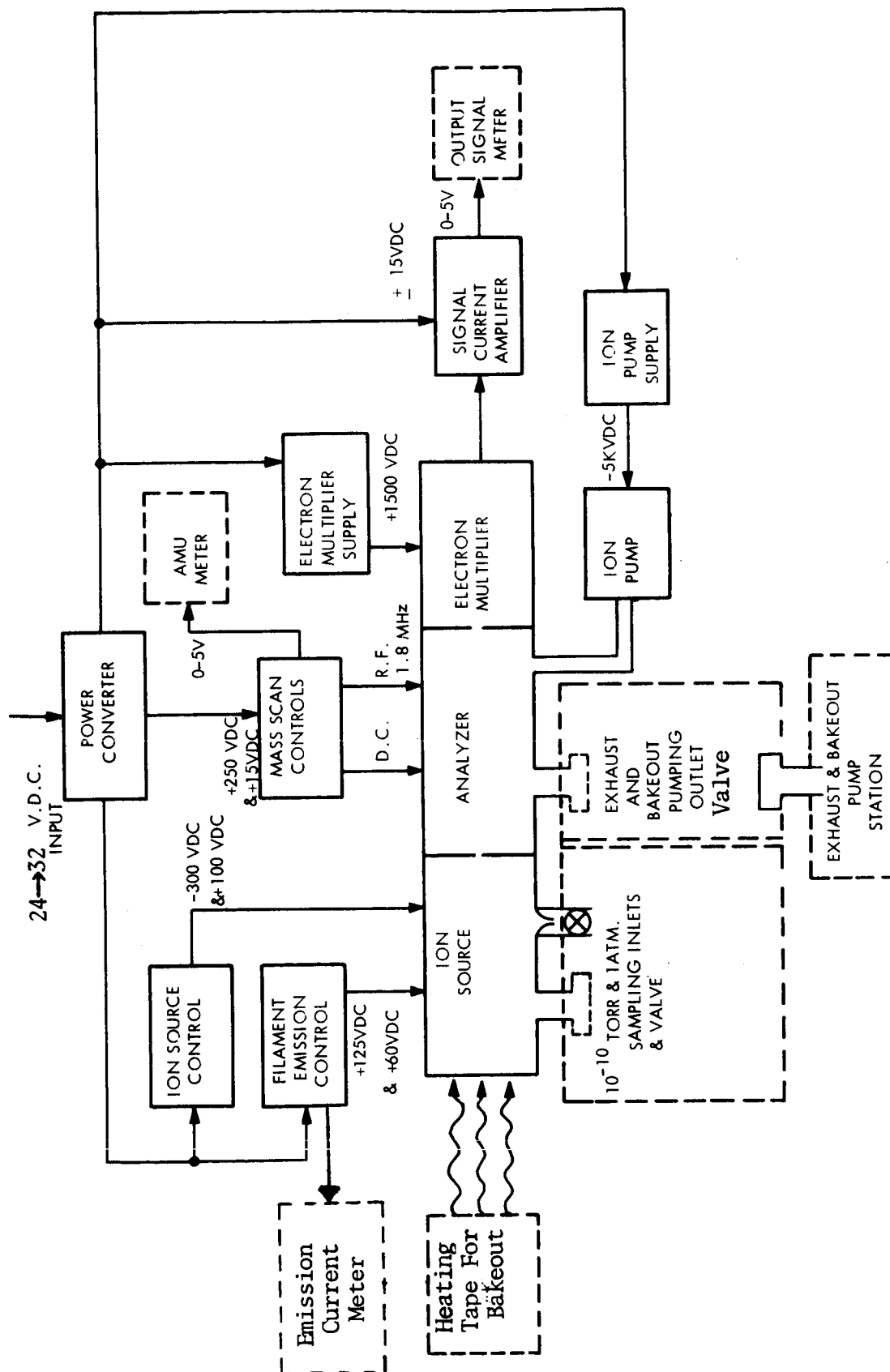


FIGURE 1. EQUIPMENT BLOCK DIAGRAM

The gas to be analyzed enters the ion source section of the mass spectrometer tube. The incoming molecules are ionized by electron bombardment. These ions are then accelerated into the analyzer tube and separated by a combined RF and DC field in a region which consists of a cylindrical rod and a right angle channel. For given applied RF and DC voltages only ions of one particular mass will satisfy the electro-dynamic equations of motion and reach the far end of the region. All others are filtered out and hit the rod, channel or endplate. The ions which pass through the aperture in the endplate strike the first stage of an electron multiplier causing electrons to be emitted. These electrons are multiplied in number in the succeeding stages of the electron multiplier. The current output from the electron multiplier is fed to a high gain, high impedance operational amplifier. The output of this amplifier is proportional to the partial pressure of the sampled constituent in the gas being analyzed.

The RF and DC voltages which are applied to the mass filter region of the tube are monitored to obtain a measure of the mass AMU*, for which the filter is tuned. These voltages can be swept in a sawtooth fashion to cover a desired range of masses. A plot of mass number vs partial pressure can be used by one skilled in the science to identify the chemical nature of the constituents in the sample which entered the tube. After initial analysis the succeeding identifications may be partially automated.

This is a brief description of the purpose, application, and operation of the mass spectrometer developed in this program. The remainder of this report discusses the equipment in detail. Photographs of the equipment are shown in Figure 2.

* Atomic Mass Unit

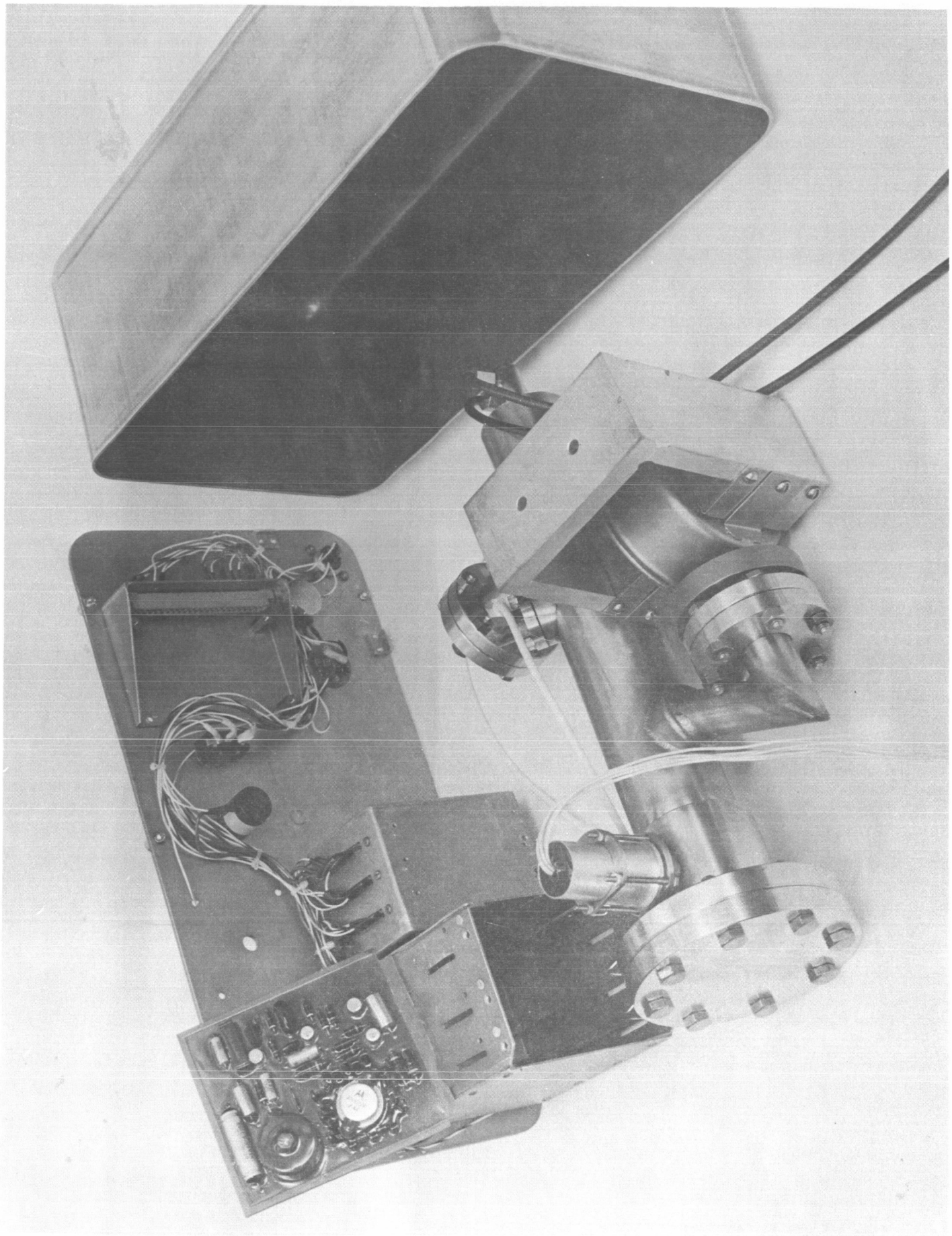


Figure 2. Flight Mass Spectrometer

III. DEVELOPMENT AND DESIGN

The performance specifications for this effort have been listed in Section II. Basically the design effort has consisted of ruggedizing and reducing the weight and power input of an existing piece of laboratory equipment. Goals were specified on the weight of each part of the equipment giving a total flight hardware weight of 16.8 lbs. The anticipated power required for each circuit function was estimated by considering the amount of power used in the commercial spectrometer controls.

There were additional performance specifications, not listed in Section II, which had to be considered in terms of the potential applications. Specifications for repeatability and accuracy were needed early in the program in order to derive related design parameters.

Repeatability of scan is particularly important in applications where automatic identification and readout are to be used. In the following analysis it was assumed that automatic identification with periodic updating in calibration was allowed in order to arrive at the needed design specifications.

To assure correct identity of a constituent's AMU* number during consecutive scans, the location of a particular AMU reading should not deviate to another AMU position. Therefore the deviation must be less than 0.5 AMU or

$$\frac{0.5 \text{ AMU}}{300 \text{ AMU}} = 0.17\% \text{ full scale}$$

The identification would be easier if the constraint were 0.3 AMU or

$$\frac{0.3 \text{ AMU}}{300 \text{ AMU}} = 0.1\% \text{ full scale.}$$

To determine design specifications from this performance specification the equations governing the operation of the spectrometer were used; see Appendix B.

* Atomic Mass Unit

Since

$$a = \frac{8eU}{mr_o^2 \omega^2}, \quad q = \frac{4eV}{mr_o^2 \omega^2}$$

Where

a, q = dummy variables
 e = electron charge
 m = ion mass
 ω = RF angular frequency
 U = DC voltage
 V = RF voltage
 r_o = rod to V block spacing

The range of a, q over which stable solutions exist is described by the graph in Figure B2.

For $\frac{a}{q} = \text{constant}$

$$\frac{\frac{8eU}{mr_o^2 \omega^2}}{\frac{4eV}{mr_o^2 \omega^2}} = \frac{2U}{V} = \text{constant}$$

Now if the ratio remains constant:

$$\frac{e}{m} = \frac{a \omega^2 r_o^2}{8U} \quad \text{where } a \text{ is that value of } a \text{ within}$$

the stability region and is fairly constant for the stable e/m ratios, then

$$\frac{eV}{m} = \frac{a \omega^2 r_o^2}{8R} \quad \text{when } \frac{U}{V} = R$$

$$m = \frac{VR K}{\omega^2 r_o^2}$$

$$K = \text{constant}$$

$$= 4 e/a$$

(where the ions are
singly ionized)

The total differential of m is given by:

$$dm = \left| \frac{\partial m}{\partial \omega} \right| d\omega + \left| \frac{\partial m}{\partial r_o} \right| dr_o + \left| \frac{\partial m}{\partial V} \right| dV + \left| \frac{\partial m}{\partial R} \right| dR$$

Where

$$\left| \frac{\partial m}{\partial \omega} \right| = \frac{2 K R V}{r_o^2 \omega^3}$$

$$\left| \frac{\partial m}{\partial r_o} \right| = \frac{2 K R V}{\omega^2 r_o^3}$$

$$\left| \frac{\partial m}{\partial V} \right| = \frac{K R}{\omega^2 r_o^2}$$

$$\left| \frac{\partial m}{\partial R} \right| = \frac{K V}{\omega^2 r_o^2}$$

Since

$$\left| \frac{dm}{m} \right| = \frac{dm}{\frac{RVK}{\omega^2 r_o^2}}$$

Then:

$$\frac{dm}{m} = + 2 \frac{d\omega}{\omega} + 2 \frac{dr_o}{r_o} + \frac{dV}{V} + \frac{dR}{R}$$

By previous assumptions

$$\frac{dm}{m} \times 100\% \leq 0.1\%$$

Assuming independent and equal variations, the r.m.s. value of deviation was allowed, and the maximum allowed variations from scan to scan were specified:

$$\frac{\delta\omega}{\omega} < .025\%$$

$$\frac{\delta V}{V} < .05\%$$

$$\frac{\delta R}{R} < .05\%$$

An accuracy of 10% on the partial pressure reading was established in the applications study, in Appendix A. This accuracy requirement established design criteria for regulation requirements on the ion source control, the electron multiplier bias voltage and the output amplifier gain.

The description of development and design for the three major areas of effort (spectrometer tube, electronics and packaging) is presented in the following sections.

3.1 MASS SPECTROMETER TUBE

3.1.1 Introduction

This portion of the report reviews the development of a feasibility demonstration model of a monopole mass spectrometer suitable for space applications. The instrument was to be lightweight and rugged. The goal was to develop an instrument capable of withstanding severe vibration and hopefully capable of operating during this vibration. Both objectives have been met.

Figure 3 is a photograph of the General Electric Monopole 600. This is the most sophisticated monopole yet developed by GE and was used as a basis for designing a practical flight monopole.

Figure 4 is a drawing of the monopole showing the location of its parts. An ion source is located at the left end of the tube. The rod and V-angle block are in the center of the tube. They serve as the analyzer filter region. Ceramic balls fit in both ends of the RF pole and in plates at both ends. The plate on the right end is of 12 mil spring steel. This serves to keep the rod in place by exerting a slight compressive force. An electron multiplier is mounted at the right end of the tube to serve as a particle detector. A voltage divider resistor network is attached directly to the multiplier. The analyzer and multiplier assemblies are mounted in a cylindrical envelope. The ion source is mounted on the analyzer end plate at the left end of the envelope. In the commercial model use, the multiplier end of the envelope is mounted to electrical feedthroughs on a 4-1/2" flange. Other leads to the RF pole and ion source are insulated with glass tubing and spot welded to feedthroughs on the flange. The flange and leads can be seen in Figure 3.

3.1.2 Initial Work

The first phase of the work was to study the Monopole 600 to determine its strong and weak points, and to see where weight could be eliminated without detracting from ruggedness or performance. The major design effort was to be directed toward ruggedization so that the spectrometer could operate during the specified vibration.

The Monopole 600 minus header weighs 2 lb. 12 oz. The major portion of this is in the analyzer assembly where the RF pole weighs 4.5 oz.,



Figure 3. Monopole 600 Mounted on Header

FIGURE 4

Commercial Monopole Drawing

65D101555

(attached at rear of report)

and the "V" block weighs 1 lb. It seemed that about half of the "V" block weight could be eliminated. Some weight could also be saved by drilling additional holes in the inner envelope, but the maximum savings would be a few ounces. This meant that the vacuum jacket and feedthrus for the Flight Monopoles would have to be very light. In addition, the vacuum jacket would have to support the monopole securely even under severe vibration. The standard envelope and feedthrus could not be used because they support the monopole at only one end, leaving, in effect, a long pendulum free to vibrate. Also, glass is used as insulation on leads to the ion source of the Monopole 600. It would have to be eliminated.

In order to determine its weak points, a Monopole 600 was vibration tested. The tube was removed from its header since the header would not be present on any Flight Monopole, and it would only create stresses which the prototype would never experience.

A vibration jig was designed which held the monopole securely while it was vibrated in any of three orthogonal planes. Figure 5 shows the tube mounted in the jig. Initially the unit was scanned by a one "g" sine wave from 20-2000 Hz to locate the resonance frequencies and to determine which portions of the tube were most susceptible to resonance. The tube was then vibrated for 30 minutes at 0.005 g^2 /Hz from 20-2000 Hz random vibration to determine which points

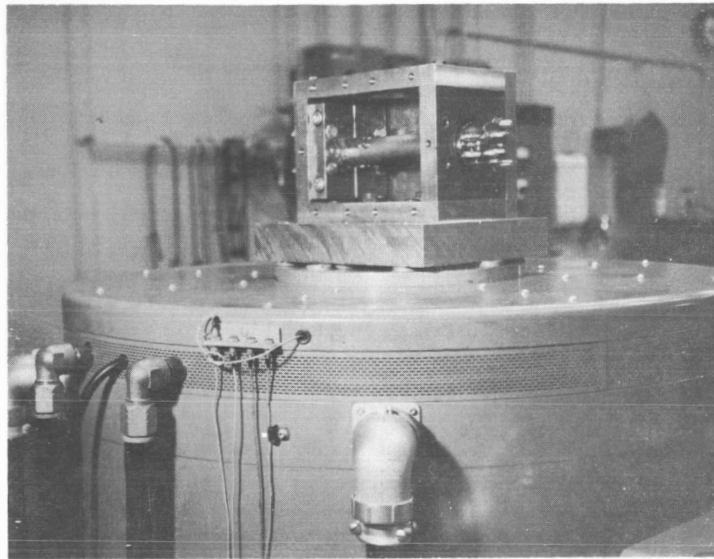
were most susceptible to failure. Before any testing a minor modification was made to the tube. Additional springs (Figure 4, part #11) were added, a washer was placed on top of the springs, and the spring clip (part #10) was spot welded in place. It was hoped that this change would hold the ion source parts more rigidly in place and prevent excessive wear from vibration. Results of the vibration tests were as follows:

Test #1 -- long axis of tube horizontal, RF pole above 'V' block - vibration vertical. Resonances were noted at 550, 970, 110 and 1680 Hz. The 550 Hz resonance was located at the ion source end plate. The other resonances were in the analyzer assembly, particularly the RF pole as it vibrated back and forth against the end plates.

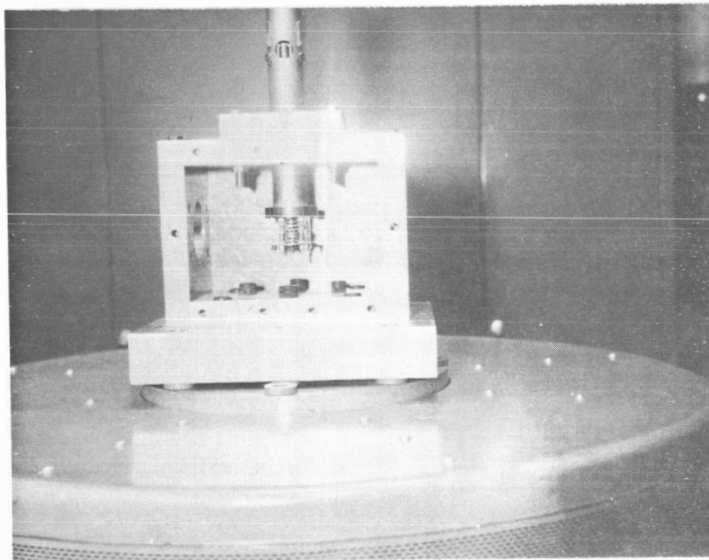
Test #2 -- long axis of the tube horizontal, rotated 90° from test #1 - vibration vertical. The analyzer assembly showed resonances at 550, 880 1100 and 1500-1800 Hz. The ion source resonated at 1450 and 1650 Hz.

Test #3 -- long axis vertical - vibration vertical. Resonance of analyzer assembly and ion source occurred at 1100 Hz. The analyzer assembly also resonated at 1220 Hz and from 1700-2000 Hz with a peak at 1800 Hz.

Random vibration at $0.005 \text{ g}^2/\text{Hz}$ from 20-2000 Hz in each of the three positions caused only minor damage. One filament broke where it had been welded to its support lead. The entire RF pole rotated slightly as did the ceramic balls used as support at both ends. When the balls rotated they picked up bits of metal which could cause a conductive path between the rod and the 'V' block. Sharp corners broke off on a few of the spacers used in the ion



5a Long Axis Horizontal



5b Long Axis Vertical

Vibration Testing The Monopole 600

FIGURE 5

source. No serious damage resulted from the tests.

After repairing the filament, the tube was operable. The standard 12 mil spring end plate was replaced by a 20 mil plate in an effort to reduce the vibration in the analyzer assembly. A new filament deck was built using slotted filament support leads and crimping the filament in place in the slot. Again the tube was subjected to a one "g" sine wave scan from 20-2000 Hz. The resonance points shifted slightly. Again the most severe vibration problem was the vibration of the analyzer assembly, particularly the RF pole.

The tube was then subjected to random vibration at a level of $0.09 \text{ g}^2/\text{Hz}$ from 20-2000 Hz for several minutes in each plane. This level was picked as the highest level the tube would see when mounted on suitable isolators if the isolators were subjected to $0.6 \text{ g}^2/\text{Hz}$ over the same frequency interval. The following defects were noted:

Test #1 Position -

The RF pole rotated. Spacers in the ion source rotated. Ceramic flakes chipped from the electron multiplier support.

Test #2 Position -

More ceramic chips and dust appeared. The ceramic balls at both ends of the RF pole looked dirty due to metal drag while rotating.

The RF pole rotated. Spot welds in two eyelets on the electron multiplier base broke after 21 minutes.

Test #3 Position -

An ion source support rod broke after six minutes. The RF pole rotated violently. When the tube was removed from the test fixture, it became apparent that the ceramic balls supporting the RF pole were severely worn. The tube was completely disassembled, and the areas of damage were noted.

Serious damage occurred wherever a ceramic part was able to rotate against a metal part. Initially a small amount of ceramic dust was produced. The dust then acted as an abrasive to grind away the metal. This grinding action was most obvious in the ion source, where the spacers acted as miniature grinding wheels, and in the analyzer assembly where the diameter of the ceramic balls was decreased by 10 mils. The holes in the end plates increased in diameter so that the spring end plate could no longer adjust to hold the RF pole securely.

Damage also resulted from the "V" block vibrating against the supporting screws (Figure 4, part 16) which deformed the "V" block by 1-2 mils. The tolerance on the "V" block to RF pole spacing is $\pm .2$ mils. The deformation from vibration exceeded this tolerance.

The electron multiplier assembly survived the severe vibration with no serious damage. Initially some of the sharp corners on the ceramic base chipped away but no further damage occurred. Because brackets (Figure 4, part 14) prevented rotation of the base, there was no evidence of abrasion. Similarly, the ceramic spacers (part 8) caused no problem. Two spot welds connecting

multiplier leads to eyelets in the base broke. However, the eyelets were more free to vibrate than they would be in any operating tube where they would be held snugly by feedthru pins. Thus the welds should be no major problem. The electron multiplier itself, including its attached resistor network, was undamaged by the vibration.

None of the metal parts in the ion source were damaged except where ceramics had rotated against them. Even the filaments survived intact when crimped in place in slotted leads.

In an operating tube, the RF pole would be prevented from rotating by a lead attached to the top of it on the electron multiplier end. This would eliminate some of the wear since the balls would be less likely to rotate by themselves, but abrasion would be a problem.

3.1.3 Flight Monopole Design

Vibration tests on the Monopole 600 indicated that attention should be focused on eliminating the rotation of ceramics in the ion source and analyzer assemblies and on eliminating at least some of the resonances found in the analyzer assembly.

Figure 6 is a drawing of the two models of the flight monopole in final form. The major design changes incorporated in the Flight Monopole are:

1. Ion Source

- (a) The ceramic support rods (part 36) are of one piece rather than two pieces glued together as on the Monopole 600. All sharp corners are slightly rounded to prevent

FIGURE 6

Flight Model Monopole Drawing
65E100092

(attached at back of report)

small pieces from chipping off. A flat is ground on the outer end against which a wire is spot welded in order to prevent the rod from rotating.

- (b) All quartz spacers (parts 37, 38) are polished on those surfaces in contact with metal and their sharp corners are radiused.
- (c) The filament support leads are slotted. The filament is dropped in place in the slots, the slots crimped and then a spot weld is made through the crimped portion to further secure the filament.
- (d) The retaining plate and retaining ring are combined into a single piece (part 46).
- (e) The outer ends of the metal ion source support rods are threaded so that the entire ion source is tightly screwed together. The nuts (part 47) that fit on the rods are then spot welded in place. By eliminating the springs used in the Monopole 600, the ion source is less free to vibrate in discrete parts. It may still vibrate as a unit, but the movement of individual parts against each other should be greatly reduced.

2. Multiplier Assembly

- (a) The sharp corners on the multiplier support are radiused to reduce the possibility of chipping. A nonfunctional groove is eliminated.
- (b) The anode of the multiplier is locked in place by a wire to prevent vibration and noise.

3. Analyzer Assembly

- (a) Weight is removed from the "V" block by machining at the sides so that it has a "Y" shaped cross section.
- (b) The assembly is supported by two sets of set screws to lessen the amplitude of some of the vibration.
- (c) The RF pole is made of hollow tubing to reduce weight. Since less mass is vibrating, the wear due to abrasion should be reduced and the resonant frequency of the rod vibrating against the spring end plate should be increased.
- (d) Two methods of RF pole support are utilized. For model #2, a 31 mil spring end plate is used. Sapphire balls replace the standard ceramic balls to reduce metal drag in case the balls should rotate during vibration.

In model #1, the RF pole is supported by split ceramic rings. A fastener expands the end of the pole against the rings which are in turn forced against the end plates. The spring end plate is eliminated. The support is the same at both ends of the rod. This method has the advantage of replacing the relatively flexible spring end plate by a stiff plate. Also, the ceramic spacers are well shielded from the ions being analyzed. The disadvantage is that this system cannot react to take up space caused by wear as a spring end plate can. Thus, if one of the fasteners loosens slightly or if the ceramic spacers ever wear, the RF pole will become loose and the performance of the tube will suffer. However, vibration is less likely to occur than with the spring end plate. By utilizing two designs, the one which in practice proves better can be chosen after testing. If both perform equally, then the decision of which to use in the future can be made on other than performance grounds.

- (e) The ion source end plate is designed to screw directly into the support ring on the end of the envelope. This prevents the possibility of rotation of the combined analyzer-ion source assembly relative to the envelope and multiplier assembly during vibration.

4. Inner Envelope Assembly

- (a) A series of 21 - 3/4" diameter holes are drilled in the inner envelope to reduce its weight. These holes also provide increased conductance for more rapid pumping.
- (b) Two slots are milled in the outer diameter of the support ring to reduce weight and to increase the conductance to the ion source area.

All changes from the Monopole 600 design were made for one of two reasons - either to produce a more rugged structure in which individual pieces would be unlikely to vibrate separately and cause wear, or to reduce the weight of the standard tube.

3.1.4 Design of the Vacuum Jacket

The vacuum jacket for the flight monopole has to fulfill the following requirements:

- (1) Be rugged enough to withstand severe vibration.
- (2) Hold the monopole securely during vibration.
- (3) Be lightweight.
- (4) Have the necessary feedthrus for electrical connections.

- (5) Provide the necessary parts for the lab exhaust system, sustaining pump and sampling system.

The final design consists of a piece of 2-1/8" OD tubing about 11" long. One end is welded to a flange on which are mounted two feedthrus for the high voltage and collector connections to the electron multiplier and a grounding pin. When the monopole is mounted in the tube, the base of the multiplier accepts the feedthrus and pin and in turn they prevent the monopole from rotating. The other end of the tubing is welded into a 2-1/2" OD tube which, in turn, is welded to a specially prepared 4-1/2" flange. A collar fits onto a shoulder on the ion source support ring of the monopole, locks in position with a dowel pin, and then is screwed to a milled-out ring on the flange. The collar supports the ion source end of the monopole and also prevents the tube from rotating within the vacuum jacket. Two slots are milled in the collar to coincide with similar slots in the ion source support ring. These slots increase the conductance to the sustaining pump. When mounted in the vacuum jacket, the tube is so oriented that a line passing through the center of both the RF pole and "V" block makes a 45° angle with a perpendicular.

A short length of 1-1/2" OD tubing (part 10) is mounted on top of the jacket near the multiplier end. It ends in a 2-3/4" flange and is intended to be used as a port for connection of the laboratory exhaust system. If the tube were actual flight hardware, the tubing would be replaced by a pinch-off. A second piece of 1-1/2" OD tubing (parts 11, 12) is welded to the bottom of the jacket at the ion source end. The tubing is welded to form a 90° bend and a 2-3/4" flange is attached. The sustaining pump is connected here.

When a vibration test is run, the flange is blanked off, since the sustaining pump has not yet been ruggedized. Were the pump ruggedized it could be welded directly to the tubing, thereby eliminating the weight of a flange pair.

A seven pin ionization gage header (part 7) is located on a short piece of tubulation welded to the 2-1/2" OD tube. This provides the feedthrus necessary to operate the ion source. The center pin is not used. A plug clamps securely onto the header. The leads from the header to the ion source pass through one of the slots milled in the collar, and where necessary, they are insulated with teflon tubing to prevent short circuits.

The feed thru for the RF pole is located directly above the multiplier end of the pole. A flange is welded to the 2-1/8" tubing. The feedthru itself is mounted in a second flange which is bolted to the one on the tube after an eyelet on top of the RF pole has been centered in the opening. A copper gasket provides the required vacuum seal. The feedthru prevents the pole from rotating during vibration.

The high voltage, collector, and RF feedthrus are all potted to provide more ruggedization and to reduce the possibility of corona at reduced pressure. Suitable leads are attached to each feedthru.

A blank flange can be mounted on the 4-1/2" flange for high vacuum testing or the tube can be connected to a UHV* system by the flange while the two 2-3/4" flanges are blanked off for low ambient pressure sampling. For atmospheric sampling, a leak mounted on a 4-1/2" flange is attached. Initially both sides of the leak are

* UHV - Ultra High Vacuum

evacuated and then the outer side is opened to atmosphere for the actual testing. In an actual flight model, the 4-1/2" flange pair could be eliminated and the leak welded in place over the ion source end, which would reduce the weight.

3.1.5 Construction and Testing the Flight Monopoles

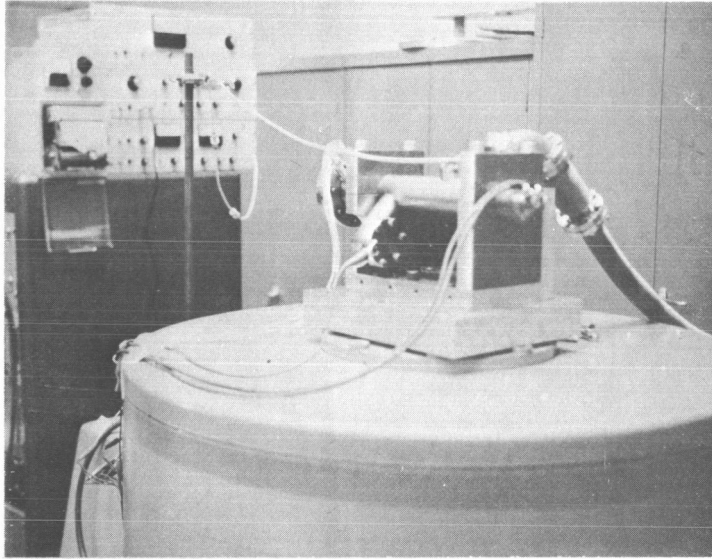
In order to be able to electrically test a tube at the earliest possible date, the ion source, analyzer, and multiplier assemblies for Model #1 - the tube in which the RF pole is supported by split ceramic rings - were assembled and placed in a Monopole 600 envelope on a Monopole 600 header. Being able to do this was an unforeseen advantage, as the working portion of the tube was finished several weeks before the vacuum jacket and the envelope were complete. The tube's performance in the standard envelope was thought to be a good indication of how it would perform in its own envelope and vacuum jacket.

Initial tests were promising. Sensitivity was adequate and resolution was excellent. There was less than a 10% valley between peaks out to beyond mass 300. The only problem was dirt. There was a peak at virtually every mass number from 40 to above 300. Heating the tube to 150°C helped to reduce the pressure somewhat, but the high mass peaks still persisted, even after a weekend. Raising the temperature to about 250°C destroyed the tube's performance. Upon disassembly, it was apparent that dirt from the inside of the hollow RF pole had coated some sections of the pole with an insulating layer. A thorough cleaning removed most of the dirt. The tube was reassembled in the Monopole 600 envelope

and again tested. Once again resolution and sensitivity were more than adequate. The high mass peaks were absent. Upon removal from the standard envelope the tube was placed in its own envelope and vacuum jacket. Both the 4-1/2" port and the port to which the sustaining pump would be bolted were blanked off.

By means of a 30" section of flexible bellows plus a short bellows and 90° elbow, the tube was connected to a vacuum system through the lab exhaust port. The system consisted of a mechanical pump, a sorption pump which was used primarily as a trap, and a 25 liter/second ion pump. The tube was then mounted in a vibration jig, evacuated, and operated. As positioned in the jig, the tube was vibrated in a plane passing through the center of the RF pole and V block along their long axis. Figure 7 shows the tube in the vibration jig.

A spectra taken before the tube was vibrated indicated the system was clean and the tube was functioning well. A sinusoidal scan was made from 20-2000 Hz at a one "g" level in order to determine the resonant frequencies. At 206 Hz the end of the tube at the 4-1/2" flange resonated. This low frequency was due to the method of tube support in the vibration jig. When the support was moved nearer to the flange, the resonant frequency increased to 306 Hz. It was expected that, when mounted in the final package in which the tube would be supported at three places, this resonant frequency would be further increased.



Vibration Testing The Flight Monopole

Figure 7

Other resonant frequencies were noted at 1097, 1560, and 1764 Hz. These higher frequencies appeared to originate in the analyzer assembly. While the scan was being made, an oscilloscope trace of masses 16-18 was run at .5 sec/sweep. The masses could be distinguished at all but the resonant frequencies. However, an approximately 20% loss in sensitivity occurred during the scan. After the scan a spectra was taken. Resolution and peak shape had not changed. The unit was then run at a random vibration level of $0.005 \text{ g}^2/\text{Hz}$ from 20-2000 Hz while a spectra from mass 1-50 was taken in order to see if it would be feasible to operate the tube during vibration. Although the peak shape degenerated slightly as the mass increased, there was better than unit resolution over the range. A spectra taken after vibration indicated that the random vibration had not permanently affected the tube's performance. The vibration level was increased to $0.09 \text{ g}^2/\text{Hz}$ from 20-2000 Hz while a spectra was taken. After approximately two minutes at this level, a leak developed so the system had to be shut down. Masses 1-20 had been scanned at the time the leak developed. Resolution was still better than unity over that range.

The leak was located at the weld joining the laboratory exhaust tubulation to the vacuum jacket. After removing the monopole from the vacuum jacket, the leaky area was rewelded and all other welds were reinforced by additional exterior welding. Meanwhile, one of the filaments which had been ruined by rapid exposure to the atmosphere

was replaced. At this time it was realized that the tubulation leading to the sustaining pump was located in the wrong position. To save time, the second vacuum jacket was made up with the tubulation in the correct position. Model #1 was mounted in this jacket. At the same time, a low noise cable was attached to the collector feedthru in an attempt to cut down on excess noise caused by cable movement during vibration of the tube.

The monopole was again mounted in the vibration test jig and pumped down. A one "g" sine wave scan indicated resonances at 220, 1270, and 1670 Hz. Again, the low resonance was expected to be increased when mounted in the final package. After 2 minutes 20 seconds at the $0.09 \text{ g}^2/\text{Hz}$ level, one filament broke and a metal strip from the eyelet on top of the RF pole fell into the multiplier causing a short circuit. The tube was disassembled and the filament, which had evidently been weakened by rapid exposure to atmosphere in the previous test, was replaced. After further evaluation of vibration level reduction capability of the isolators, the tube was operated while vibrating at the reduced level of $0.09 \text{ g}^2/\text{Hz}$ from 20-500 Hz and $0.035 \text{ g}^2/\text{Hz}$ from 500-2000 Hz. Although sensitivity and resolution were reduced during vibration, one could see individual peaks through mass 44. As noted earlier, resolution decreased at higher masses. Spectra taken before and after vibration indicated no permanent damage could be attributed to the vibration. Flight Monopole model #1 was shipped to ASD for further testing on March 21, 1968.

While model #1 was being placed in its vacuum jacket, model #2, using sapphire balls to support the RF pole, was assembled in a monopole 600 envelope for initial testing. Although the tube had been thoroughly cleaned, initial spectra showed many hydrocarbons at high masses were present. However, resolution was excellent and sensitivity was adequate. The tube was heated gently at first to 120°C, then at 150°C, and finally at about 200°C. Ten days of this treatment eliminated most of the dirt without impairing the tube's performance.

After the leaks in the first vacuum jacket were repaired, the tubulation to the sustaining pump was cut off 1/2" from the 2-1/8" OD tube. 1" OD tubing was cut and welded in place so as to move the flange to the sustaining pump one inch closer to the 4-1/2" flanged end of the vacuum jacket, where it should have been in the first place. Model #2 was removed from the Monopole 600 envelope and assembled in its vacuum jacket. After being placed in the vibration test jig and pumped down, it was operated prior to being vibrated. Resolution, peak shape, and sensitivity were all good. At a one "g" sine wave scan, resonances were noted at: 235 Hz - 4-1/2" flanged end of the tube, 550 (minor), 1250 to 1350, and 1700 Hz. As with model #1, the high frequencies were due to vibration of the analyzer assembly. The 550 Hz resonance could not be located precisely, but seemed due to the method of mounting the tube in the vibration jig. Spectra taken before and after vibration indicated a slight loss in sensitivity, but no change in peak shape or resolution. The tube was then vibrated at $0.09 \text{ g}^2/\text{Hz}$

from 20-500 Hz and $0.035 \text{ g}^2/\text{Hz}$ from 500-2000 Hz while a spectra was taken. As with model #1, peak shape deteriorated with increasing mass. However, sensitivity was approximately the same as before vibration and individual peaks could be seen beyond mass 44. A spectra taken immediately after vibration showed no evidence of a degradation of tube performance due to vibration. Flight monopole model #2 was shipped to ASD on April 4, 1968.

Copies of the spectra taken before, during, and after vibration for both models are shown in Figure 8 for model #1, and Figure 9 for model #2.

At the same time model #2 was shipped, two metal leaks mounted on 4-1/2" flanges were sent. These are to be used for atmospheric sampling. Also included were two Hoke valves brazed to A & N couplings. The couplings will be used to provide a seal to the leaks. When the system is to be pumped down, both sides of the leak will be evacuated and the valve closed. Opening the valve will allow atmospheric sampling. The coupling and valve will be disconnected from the leak to allow for atmospheric sampling while vibrating.

Spectral Data Before Vibration Tests
Model #1 - Split Ceramic Supports

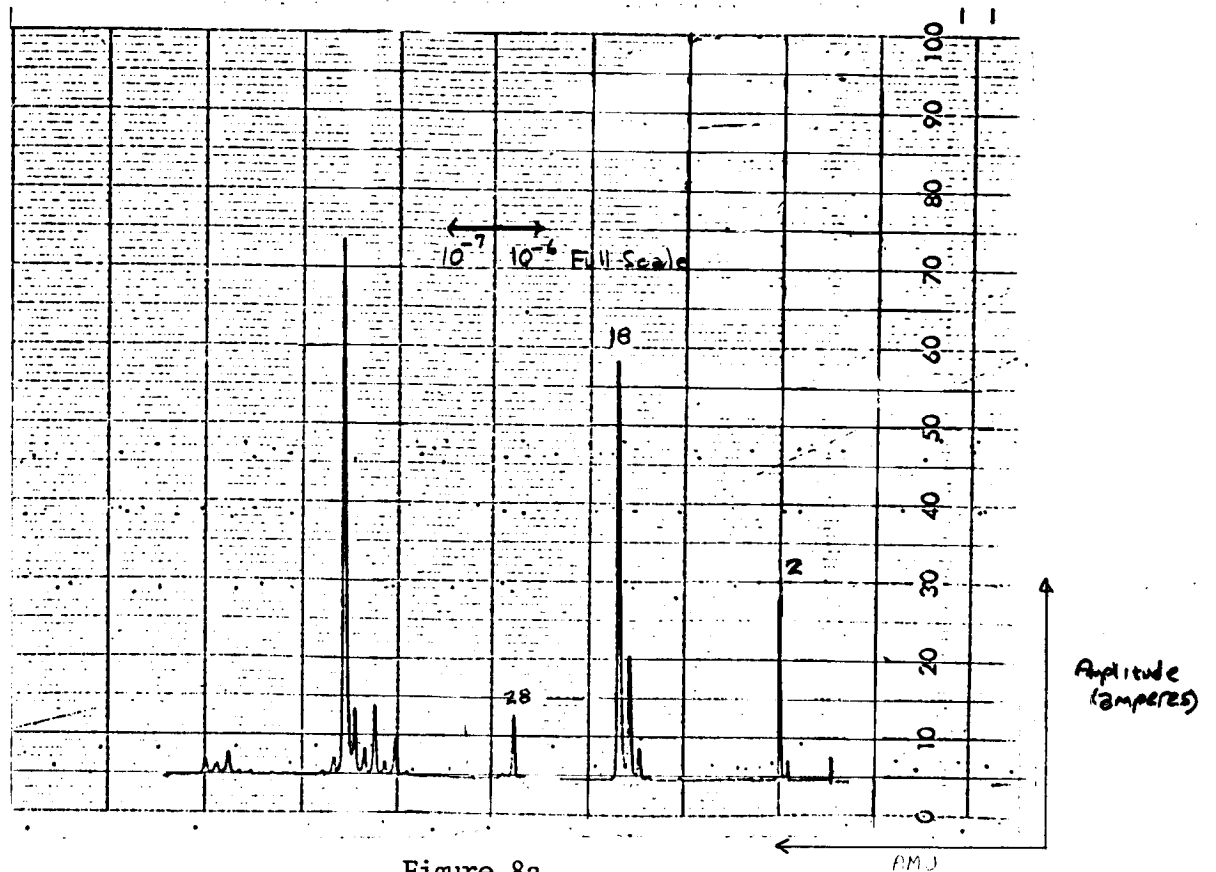


Figure 8a
Spectral Data During Vibration Tests - Model #1

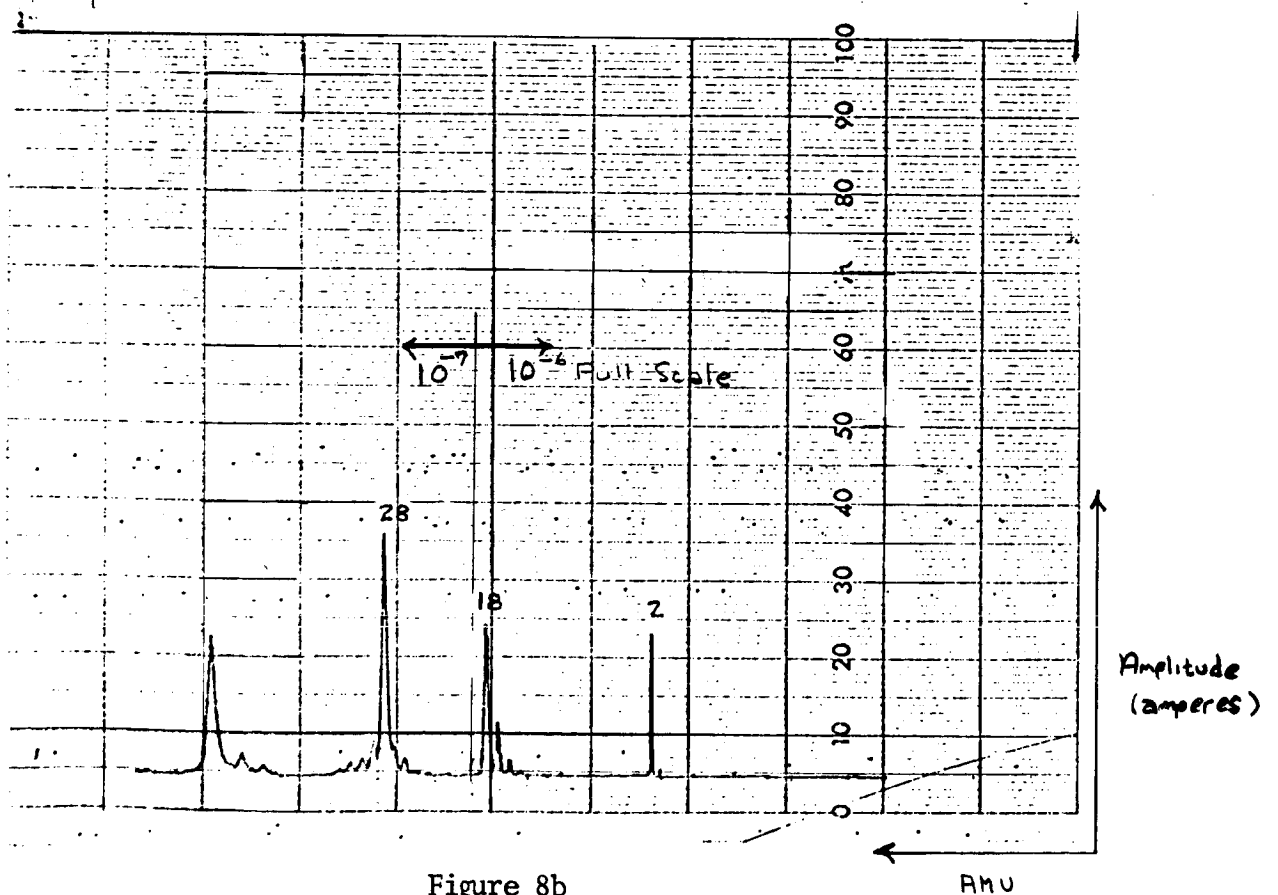
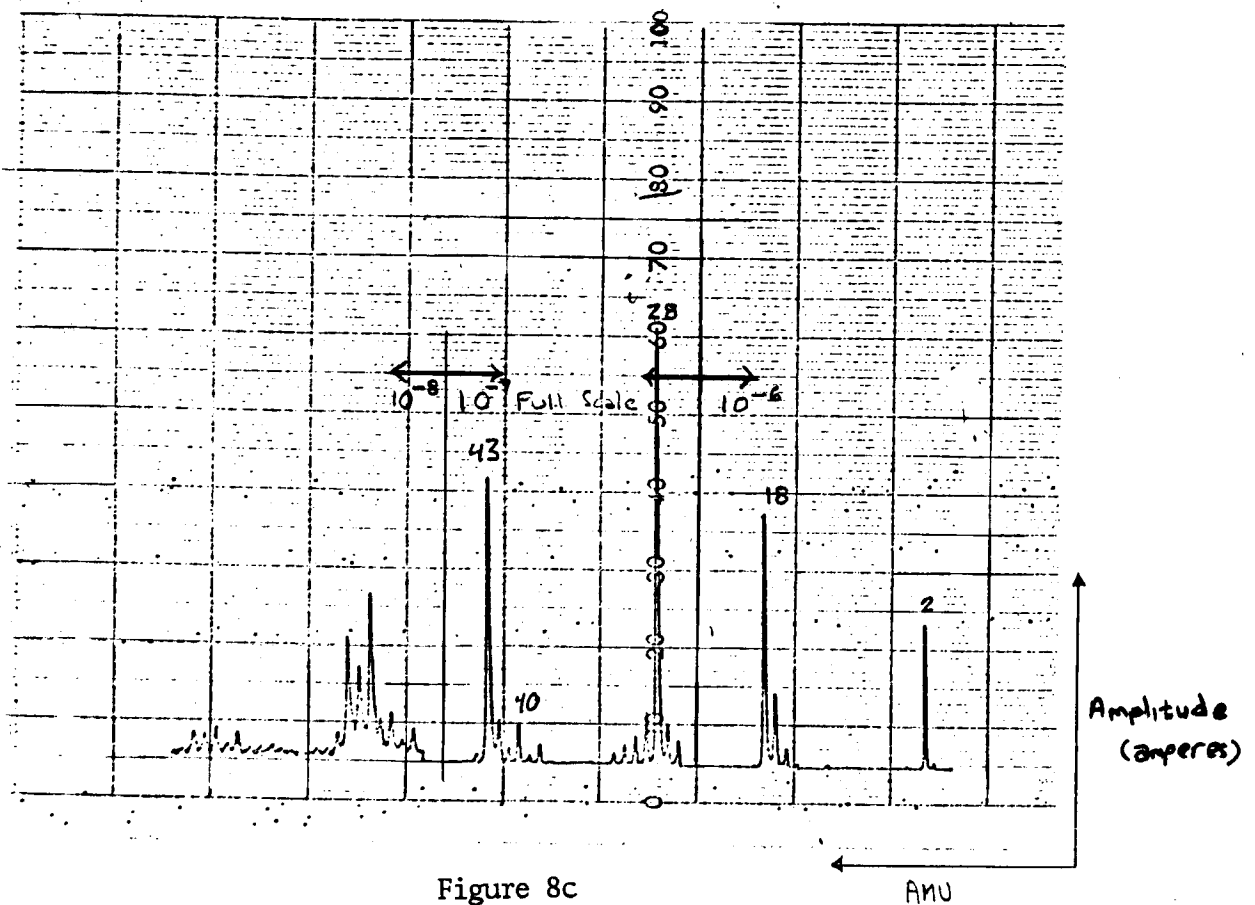


Figure 8b

Spectral Data After Vibration - Model #1



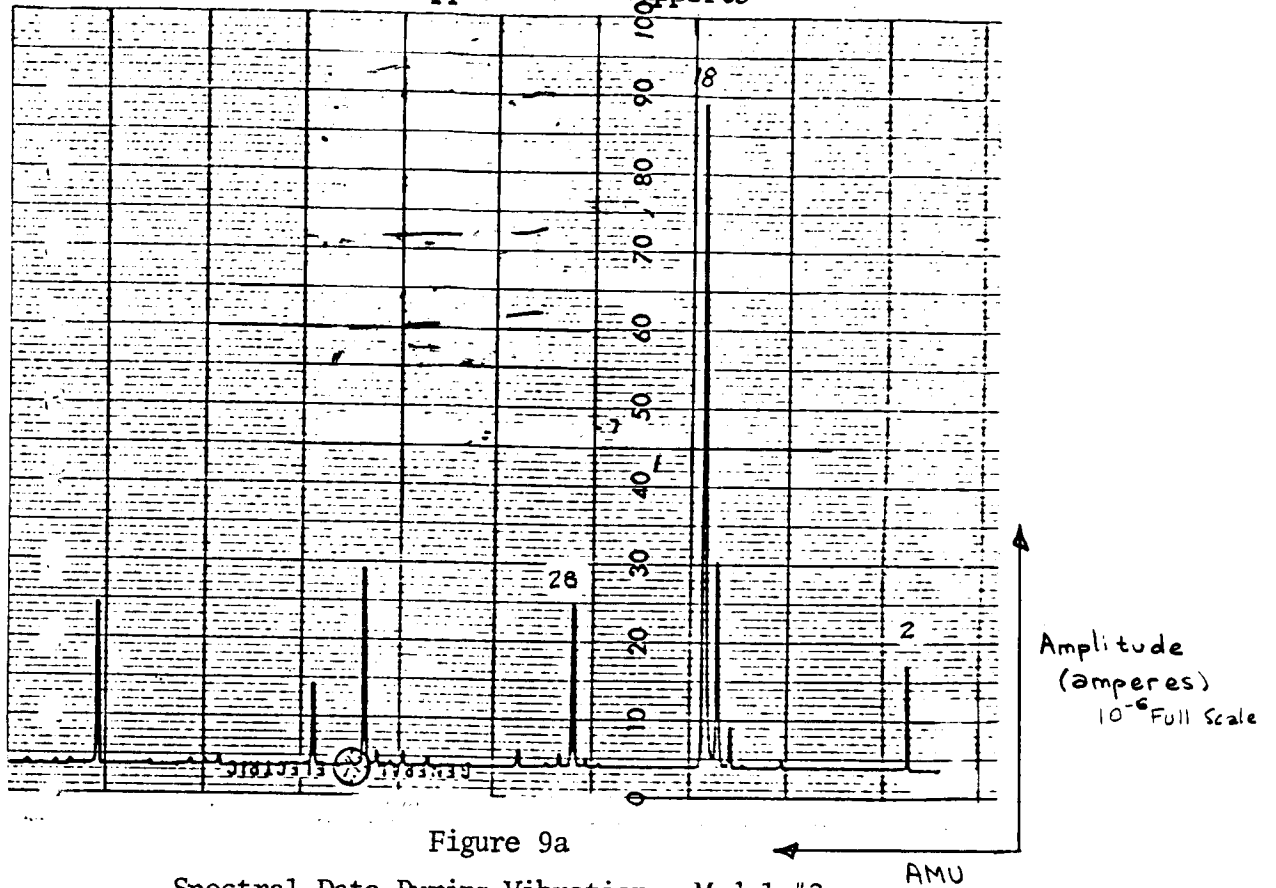
Data on Figure 8:

Emission Current: 0.33 ma
 Ionization Voltage: 70 V
 Internal Pressure: $\approx 1.5 \times 10^{-6}$ torr

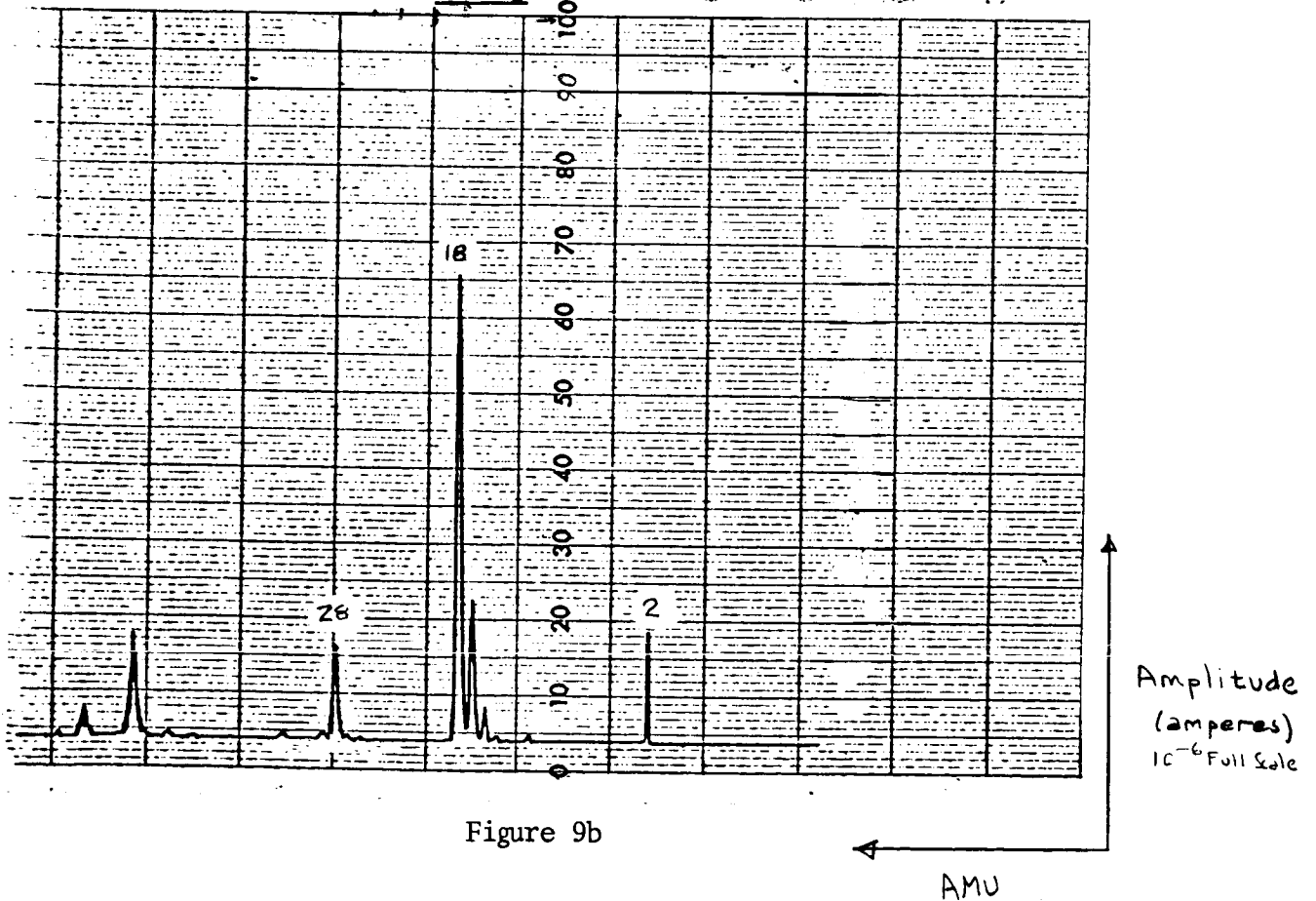
Scaling on data was varied between
 10^{-6} to 10^{-8} units full scale.

AMU identification is given about prominent peaks.

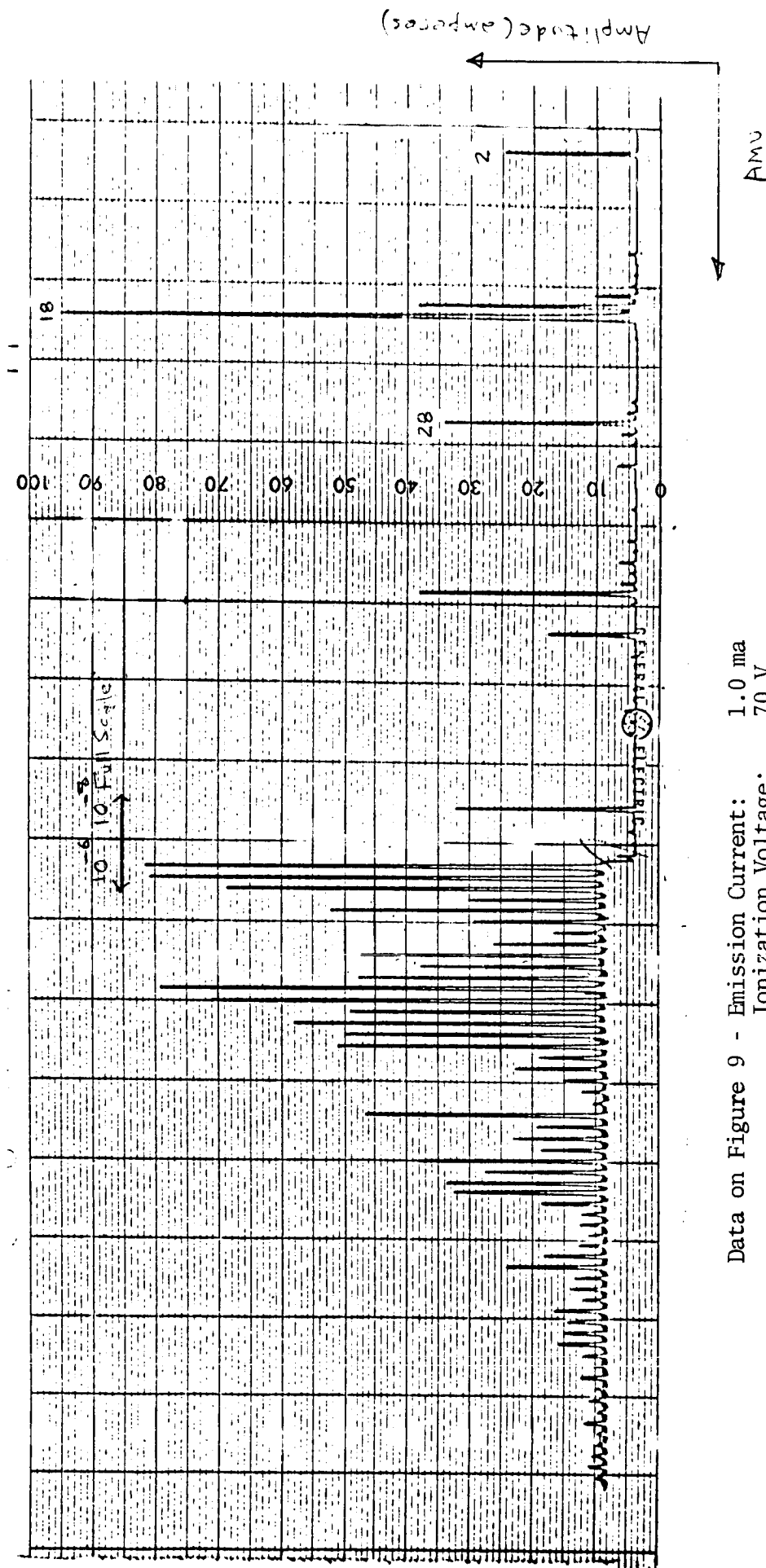
Spectral Data Before Vibration Tests
Model #2 - Sapphire Ball Supports



Spectral Data During Vibration - Model #2



Spectral Data After Vibration Tests - Model #2



Data on Figure 9 - Emission Current: 1.0 ma
 Ionization Voltage: 70 V
 Internal Pressure: $\approx 7 \times 10^{-7}$ torr
 Full Scale Range varied from 10^{-6} to 10^{-8} amps on Fig. 8c.
 AMU identification is given above prominent peaks.

Figure 9c

3.2 ELECTRONICS

3.2.1 Description of Hardware

The electronic control package of the mass spectrometer consists of the power and control circuits necessary to operate the mass analyzer tube. The circuits are all solid state to provide reliable performance and reduce size and weight. To provide access to the electronics for maintenance and calibration, circuits are mounted on printed circuit boards where possible. The boards are mounted in modules on the front panel so that they can be removed during bakeout of the analyzer tube, and the modules are located so that they occupy space around the analyzer tube for high density packaging.

Each module consists of the circuits required to perform a function of the control circuits. The four functional modules are the scan control, ion source control, electrometer amplifier and power supply. The modules are located in the vicinity of that portion of the analyzer tube where interference between control signals is a minimum. This is particularly important with respect to the electrometer amplifier. This type of construction was used to provide ease of maintenance, since this unit is a feasibility model, and still meet the vibration requirements of the contract.

3.2.2 Functional Description of Circuits

3.2.2.1 General Specifications

The control circuits provide the power, scan control, output amplifier, and ion source control for the mass analyzer. The electronics are capable of withstanding vibration of $0.6 \text{ g}^2/\text{Hz}$ random vibration from 20-2000 Hz when mounted on vibration isolators. The sensitivity of the mass analyzer tube in conjunction with the electrometer amplifier is a partial pressure measurement to 10^{-10} torr. The analyzer, when controlled by the electronics over the mass range, has unit resolution. The scan rate is approximately 60 seconds

and a manual scan capability is provided. The mass range is 1-300 AMU with a suitable readout of partial pressure for telemetry or for recording.

3.2.2.2 Scan Control Circuits

The scan control circuits provide a 1.8 MHz R.F. voltage which sweeps from 0 to 750 V peak in 60 seconds which is superimposed on a DC level having a ratio of 1:11 to the R.F. voltage throughout the sweep. The sweep is linear within ± 1 percent over the mass range. The long term stability of the R.F. and DC voltage is $\pm 0.5\%$ and that of the RF frequency is $\pm .25\%$. The short term stability and the reason for these requirements are discussed in Section III.

The 1.8 MHz voltage amplitude is controlled by a sweep generator (or manually set voltage) and a feedback control loop. A block diagram of the control loop is shown in Figure 10. The sweep generator provides a saw tooth reference voltage with about a 60 second period. The positive slope saw tooth is summed with a weighted negative feedback voltage to provide an error signal.

The negative feedback voltage is derived from the peak RF amplitude by a diode-capacitor peak detector circuit and a voltage divider. This circuit also provides the DC bias voltage for the RF output.

The error signal output from the weighted summer is amplified in the error amplifier and used to control the gain of the voltage variable gain amplifier. The output of the combined variable gain and RF amplifiers can be varied from zero to 750 volts peak RF amplitude. This output, along with the proportional DC bias voltage, provides the drive for the spectrometer tube electrodes.

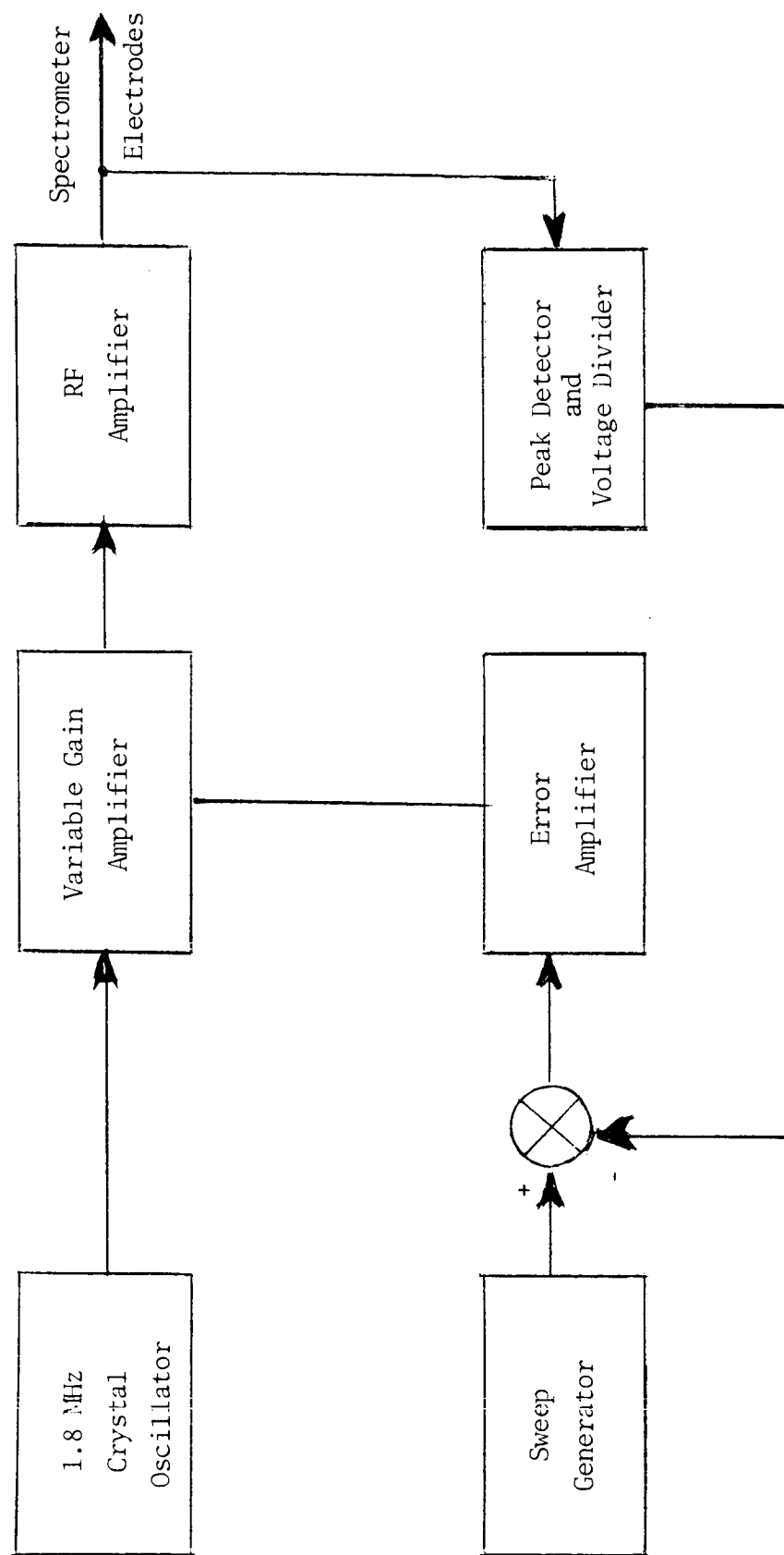


FIGURE 10
RF Amplitude Control Block Diagram

The sweep generator circuit is shown in Figure 11. The operation of this circuit is as follows: A small current flows through C_1 , the feedback capacitor, and R_1 , which charges C_1 with a time constant R_1C_1 . The change in voltage is amplified by A_1 . A portion of the output voltage is fed back to turn off Q_2 and turn on Q_1 , which in turn causes C_1 to discharge through R_2 . The output is clamped to ground to provide a 0-5V volt ramp to the error amplifier. The linearity of the sweep is $\pm 1\%$ and is limited by the leakage current in A. For increased linearity a FET input operational amplifier could be used to reduce the leakage.

The 1.8 Mhz crystal oscillator consists of a single transistor stage Colpitts type oscillator. In laboratory tests, the frequency varied 70 Hz over a -70 to 180°F temperature range. A graph of the performance of the oscillator with temperature is shown in figure 12.

The variable gain amplifier consists of a single stage dual gate MOS field effect transistor. The constant amplitude RF oscillator output is applied to one gate and the voltage gain is controlled by the dc potential of the other gate.

The control loop stability is achieved by a single dominant time constant in the error amplifier feedback circuit. The error amplifier time constant consists of

$$R_7 = 1K \text{ ohm and } C_{10} = 47 \text{ microfarad}$$

FIGURE 11

See SK-56137-382-4-107,
which is attached.

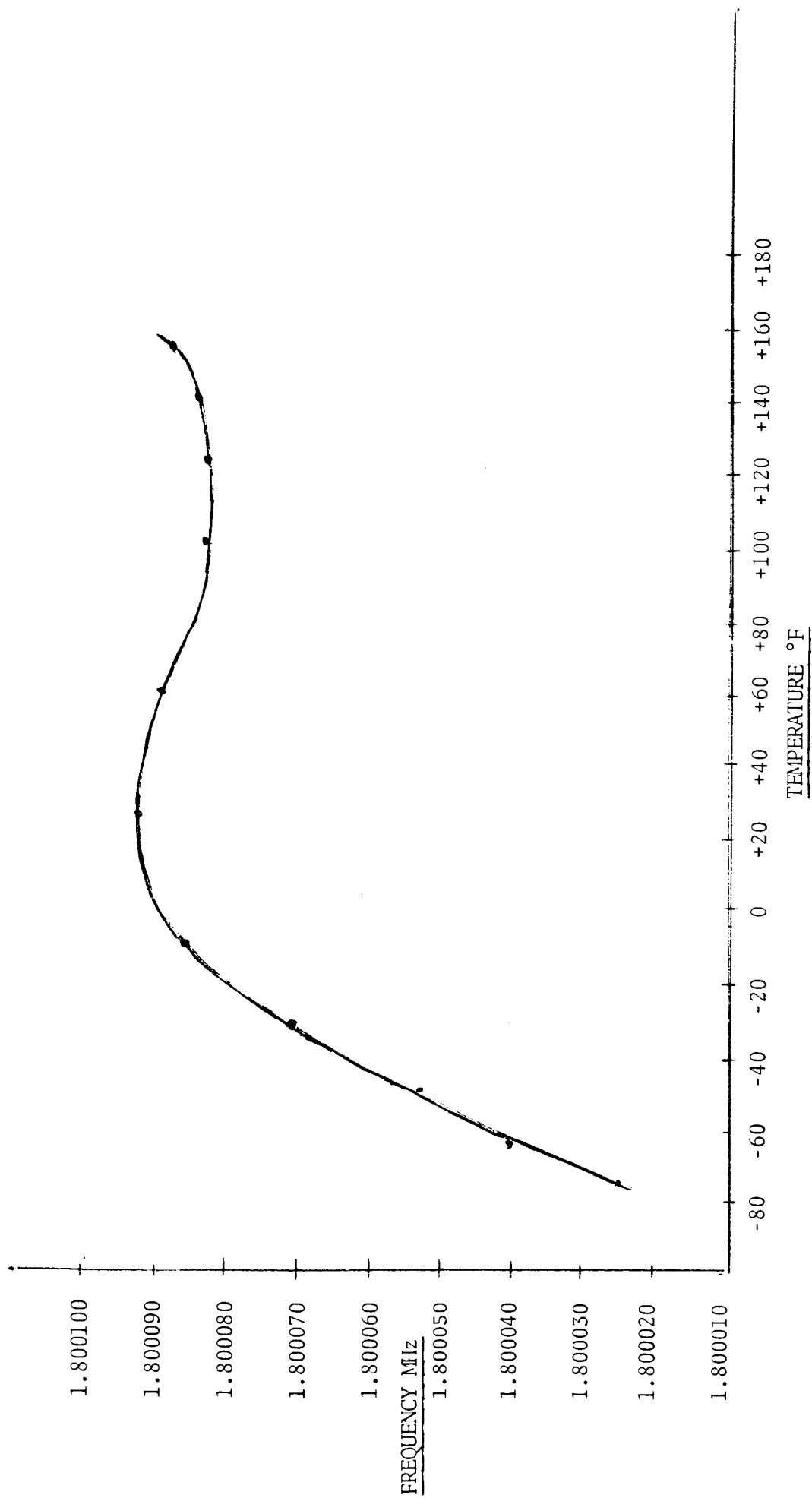


FIGURE 12

This series feedback network provides an open loop error amplifier gain at dc and a -20 db per decade slope to $\omega = 10$ rad. The gain then asymptotically approaches -26.6 db. The phase shift is -90 degrees at dc and approximately zero degrees for ω greater than 300 radians.

The dc gain is set by $R_{16} = 2.2$ megohms and $R_8 = 21.5$ K ohms or about 100. A gain of zero occurs at $\omega = 1$ radian or 0.16 Hz. Error amplifier saturation is prevented by a diode and zener diode combination in the feedback circuit.

3.2.2.3 Power Supply

The power supply must provide the voltages for the electronics, the ion pump, and the electron multiplier. Even though a regulator was not included in the original proposal, a study of application requirements showed that the input power could vary from 24 to 32 VDC. The parameter accuracy of the control circuits require that the input voltage be regulated to $\pm 0.25\%$ over the range of input voltages. The power requirements are listed in Table I.

TABLE I
Power Requirements

<u>Voltage</u>	<u>Current</u>	<u>Regulation</u>	<u>Ripple</u>
+50V	250 MA	3%	200 MV
+4.0V	1.65 MA	3%	50 MV
$\pm 300\text{VDC}$	1 MA	3%	1 V
+10V	1 MA	3%	50 MV
+70V	10 MA	3%	50 MV
$\pm 15\text{V}$	100 MA	3%	50 MV
-3000V	200 μa	3%	.33%
-5000V	500 μa	3%	.8%

Further regulation of the RF and ion source parameters are provided in the individual circuits to meet stability requirement of these functions.

3.2.2.3.1 Regulator

To provide the input regulation as efficiently as possible, a switching regulator was used. This circuit was chosen because of its superior efficiency compared to a dissipative type regulator. The efficiency of this circuit is shown in Figure 13 to be 92% at maximum power requirements where the dissipative type regulator efficiency would be 60 to 65%.

FIGURE 13

See SK-56137-382-4-102,
which is attached.

The schematic for this circuit is shown in Figure 14.

The circuit regulates the 24 to 32 VDC input to provide 23V output to the power converter with the tolerance shown in Figure 14. Q_1 is a series switch that is controlled by a Schmitt Trigger circuit Q_3 and Q_4 . The comparison circuit samples the output voltage and compares it to the zener reference CR2 and controls the Schmitt Trigger. When power is applied, Q_1 is turned on and the output voltage rises to 23 volts when the Schmitt Trigger changes state, turning off Q_1 . The output voltage decreases until the Schmitt Trigger threshold is reached and Q_1 is again turned on.

3.2.2.3.2 Power Converter

The power converter supplies all of the voltages listed in Table I from the single regulated input of the regulator. This requires that the inverter be used to drive a power transformer which will transform the inverter output to multiple outputs which are subsequently rectified and filtered to provide the DC voltages which meet the circuit requirements.

A search of the literature indicated that the most reliable and efficient converter circuit is the dual transformer negative resistance type oscillator. This circuit has many advantages over the single transformer converter. The two most important are the reduction of current spikes under light loads and the reduced magnetizing current in the power transformer. The current spikes are a major cause of transistor fatigue in a converter circuit and the large magnetizing current would greatly reduce efficiency.

To provide the high voltages (-3000 VDC and -5000 VDC) would require an impractical number of turns on the secondary of the power transformer since that same transformer must also supply 4.0 VDC. It was decided to compromise on a one volt per turn and use a voltage multiplier to obtain the high voltages from a 1000 VP-P secondary winding on the power trans-

LOAD (WATTS)

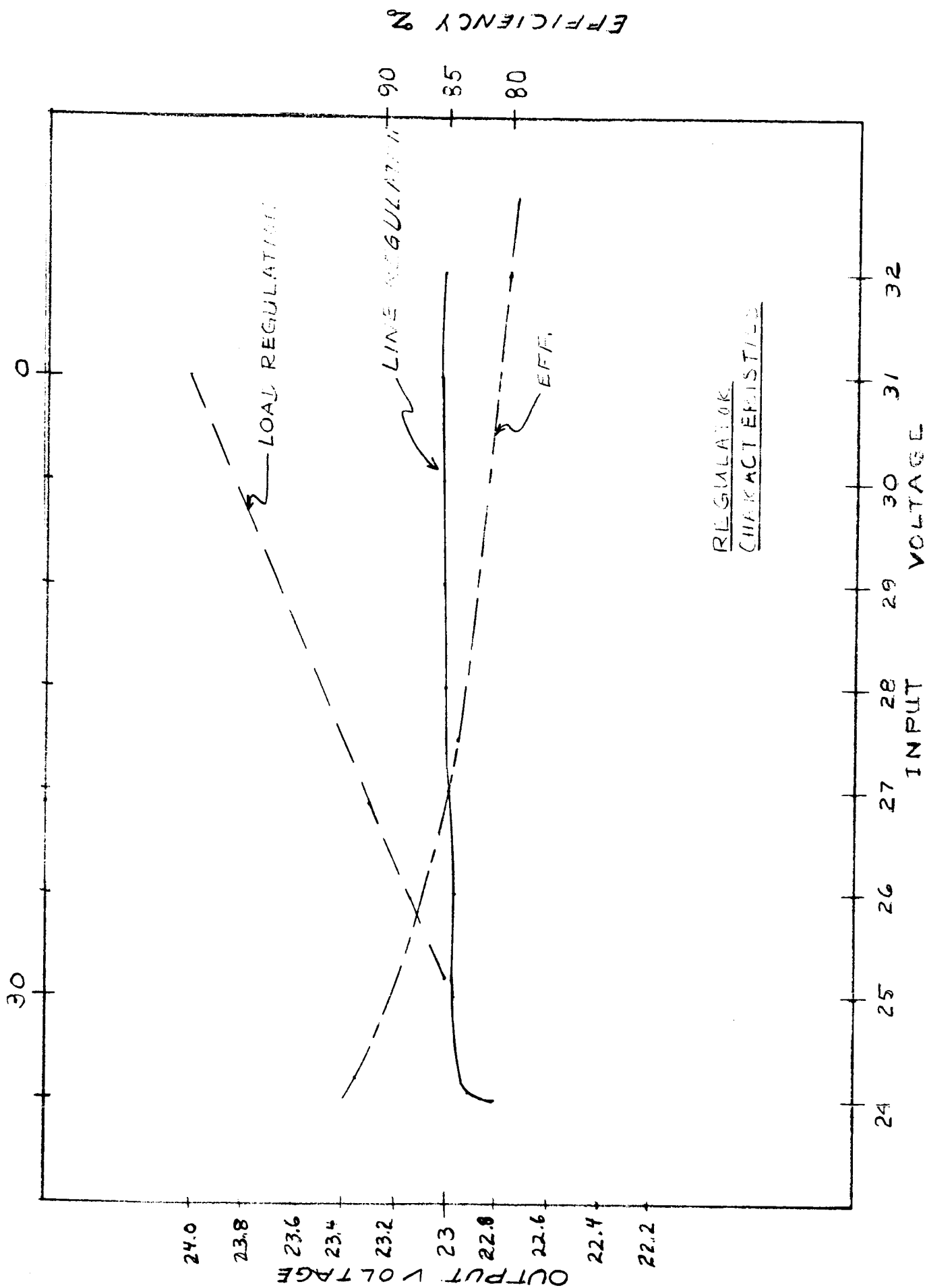


FIGURE 14

former. These multipliers were available from Erie Technological Products.

The use of these multipliers set the frequency of the converter at 12KHz to provide the required regulation of these voltages. There was some sacrifice in efficiency of the circuit due to this choice because of the low voltage high power requirements.

The circuit diagram is shown in Figures 15 and 16. The frequency of oscillation is determined from the following relationships:

$$V = 4 NA B_{sat} f \times 10^{-8}$$

where:

V = voltage on primary T-1 (46V P-P)

N = No. of turns of primary T-1

B_{sat} = Maximum flux density in gauss

f = frequency in Hz

and,

$$H = \frac{4 \pi NI}{10}$$

where:

I = magnetizing current

H = magnetomotive force in oersteds

From these equations and the equivalent circuit the circuit elements were determined. The output transformer T-2 was wound as a special transformer. The only requirements of this transformer were to keep losses at a minimum for this application. The circuit operation is basically as follows. Assume transistor Q_1 is on and Q_2 is off. The voltage across T-1 (square hysteresis loop core) causes the base of Q_2 to be driven positive causing Q_2 to be turned off. This is repeated to affect oscillation at a frequency (approximately 12 KHz) determined by the characteristics of T-1. The outputs of T-2 were then rectified to provide the supply voltages. The performance of this circuit is shown

FIGURE 15

See SK 56137-382-4-104,
which is attached.

FIGURE 16

See SK 56137-382-4-105,
which is attached.

in Table II below.

TABLE II
Converter Output

<u>Supply</u>	<u>Voltage</u>	<u>Ripple</u>
+4 VDC	3.80 V	20 MV
+50 VDC	50.2 V	40 MV
+300 VDC	325 V	20 MV
-300 VDC	324 V	20 MV
+70 VDC	70.8 V	20 MV
+10 VDC	11.2 V	10 MV
+15 VDC	16.1 V	20 MV
-15 VDC	16.0 V	20 MV

This performance either meets or exceeds the original goals for each supply voltage.

3.2.2.4 Filament Regulator and Divider Network

A functional block diagram of the circuit is shown in Figure 17, and the schematic is shown in Sketch 106. The operation of the current regulator

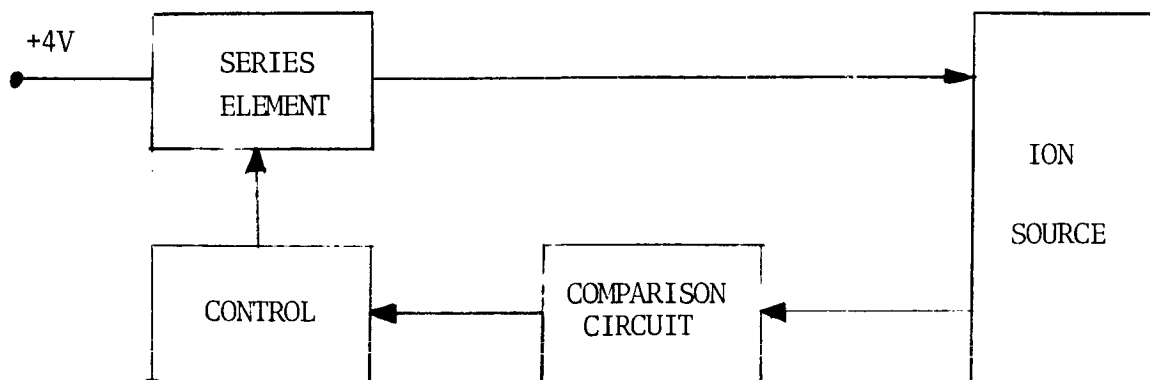


Figure 17

is as follows. The filament current is supplied through the series element Q_1 and the cage or emission current is proportional to the heating of the filament. This current is fed back and compared to the filament current in a comparison circuit. The comparison circuit output controls series element varying the drive to Q_1 Q_2 . The cage (anode) current is then controlled to a pre-set value which is adjustable by the Ion Source Control on the front panel. The gain of the control loop is determined by the combined gain of Q_1 Q_2 Q_3 which is approximately 10^5 . This circuit met the required performance.

3.2.2.5 Electrometer Amplifier

This circuit provides an accurate current measurement to 10^{-10} amp, with switched decade ranges plus a logarithmic range. (Highest current 10^{-5} amp). The feedback type picoammeter analysis follows:

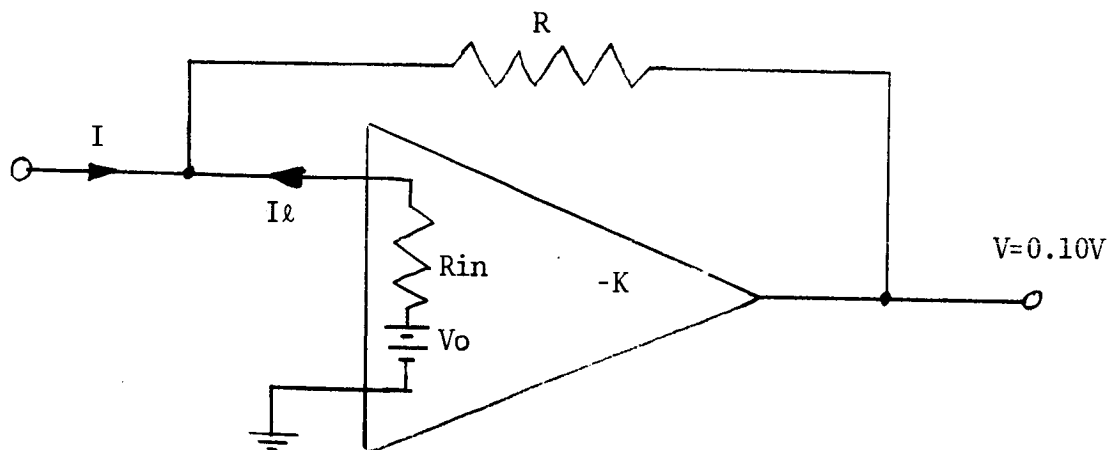


Figure 18

In an ideal amplifier, $K = \infty$, $R_{in} = \infty$, $I_l = 0$, $V_o = 0$.

For 10 volts full scale output:

$R = 10^{11} \Omega$ for 10^{-10} A full scale

to $R = 10^6 \Omega$ for 10^{-5} A full scale

Sources of error.

1. R : If R varies from the calculated value for a given range by $P\%$ this will cause an error of $P\%$ of the indicated reading.

2. Offset voltage, V_o : This will give an error, on each range, of $\frac{V_o}{10} \times 100\%$ of full scale, plus an error of $\frac{V_o}{R_{in}}$ amperes on all ranges.
3. Finite gain, K : The error will be $\frac{100}{K} \%$ of reading, on all ranges, plus $\frac{10}{KR_{in}}$ amperes.
4. Leakage current I_l : The error will be I_l on all ranges.

Several potential amplifiers were considered. The evaluation of two of these is shown. The evaluation of the Philbrick PP25A Premium Grade FET Operational Amplifier for this application follows.

1. R : Assume R is 1% resistor (difficult for high values involved).
The error = 1% of the reading on all ranges.
2. V_o : 6 mv maximum gives .06% of full scale on each range, plus $(6 \times 10^{-3})/10^{11} = 10^{-14}$ A on all ranges.
3. K : $K = 30,000$ minimum which gives an error of .003% of the reading, plus 3×10^{-15} A at full scale on each range.
4. I_l , at 75°C is 5×10^{-9} A.

Although all other errors are acceptable, the leakage current at high temperatures is too great for this application.

The Analog Device Model 302 Varactor Bridge Operational Amplifier evaluation for this application follows.

1. Same as item 1 above.
2. V_o : $60 \mu\text{V}/^\circ\text{C}$ gives 7.8 mv for the required -55° to 75°C range (essentially the same as above).
3. K : $K = 10,000$ minimum which gives an error of .01% of the reading, plus 10^{-14} A at full scale on each range.

4. $I = 16$ picoamps at 75°C . The desired maximum sensitivity of 10^{-11} A is 10 picoamps. The accuracy would therefore be about 20% at 10^{-10} A level. This is considered satisfactory for giving an approximate quantitative indication of trace elements.

This unit gives the desired performance characteristics which are shown in Figure 19.

On one scale, the scaling resistor R is replaced with a series string of diodes, then the V_{out} to I_{in} relation is approximately logarithmic. There will be errors, particularly with varying temperature, associated with variation in forward voltage drop for a given current. This allows everything from trace elements to maximum concentration to be indicated on one scale.

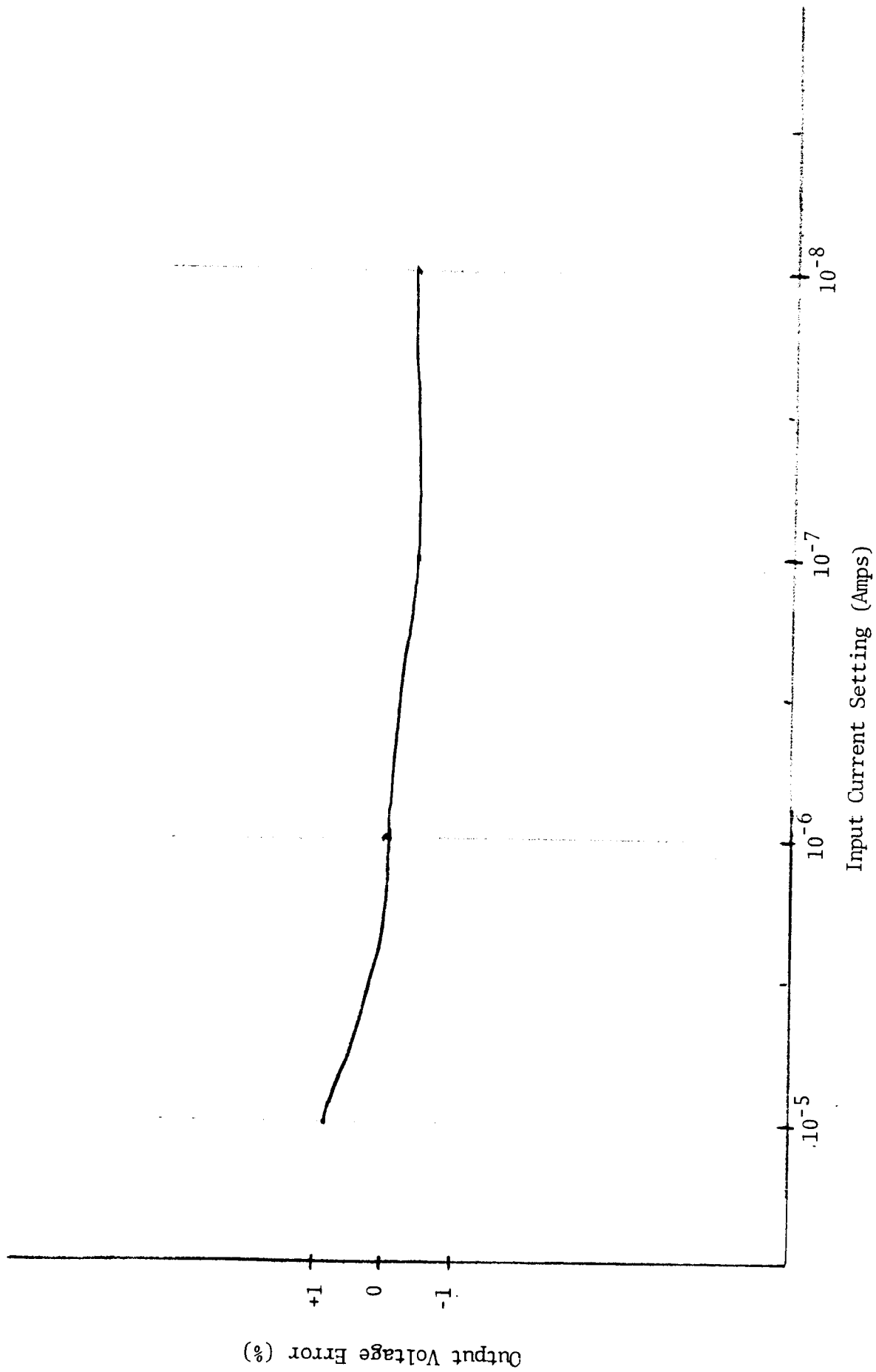


FIGURE 19. Amplifier Error

3.3 ELECTRONIC PACKAGING AND VIBRATION ISOLATION

The objective of this portion of the program was to provide a package design for the flight mass spectrometer that would permit the spectrometer to operate in the specified vibration environment of $0.6 \text{ g}^2/\text{Hz}$ spectral density random vibration in a frequency range of 20 Hz to 2000 Hz. This vibration level is equivalent to a 36 g rms acceleration, which is to be applied for six minutes duration in each plane.

In order to package a mass spectrometer to meet this rigid vibration environment, several problems had to be considered. First, the ruggedized monopole tube had to withstand a 13 g rms random vibration, i.e., $.09 \text{ g}^2/\text{Hz}$ from 20-2000 Hz without isolation mounts. This level was established as the maximum level that would be transmitted to the tube when packaged and mounted on isolators. Second, the electronics had to demonstrate the capability of operating in the package during the imposed vibration environment. Third, the electronics had to be packaged to operate remotely during the tube bake-out cycle. Fourth, the non-ruggedized Ion Pump had to be mounted in the enclosure for bench operation and remotely mounted when operating the system during vibration. Fifth, the mass spectrometer tube, ion pump, and electronics had to be contained in a case that is approximately 8 inches high, 16 inches long and 6 inches deep.

The case for the mass spectrometer is a deep drawn aluminum box, as shown in Figure 2. A check through vendor information revealed a standard case that was 8-3/8" high x 16-1/8" long and 6" deep, which is within a reasonable limit of the specified dimensions. The material used for the case was .093 inch thick, 6161-D aluminum alloy and heat treated to T6 condition after drawing.

A preliminary layout was made after the case selection to determine placement of the Mass Spectrometer tube and the ion pump. The space that could be allotted for each functional electronics group was then determined. The chassis size for each of the electronics groups was specified.

The panel is retained to the case with 8 Dzus, aircraft panel type, quick disconnect retainers. These fasteners were selected to provide quick access to the case interior. Also provided on the panel are four alignment retainers to prevent excessive movement of the panel with respect to the case during vibration.

A .032 inch thick decal overlay panel is mounted on the 0.125 inch thick panel, to identify switch and adjustment positions. The over-layer is divided into functional groups. A complete human factors study was not practical since component placement on the panel was dictated by available space behind the panel.

The power supply printed circuit boards are .093 inch thick glass material with 2 ounces copper. The heavy components to be mounted and the vibration environment demanded the use of a thick board material. All components were secured to the boards using epoxy adhesive. Conformal coating was applied to provide moisture protection. Also, the ion source control, scan control, and electrometer circuits were packaged to meet the environmental requirements.

The Mass Spectrometer tube is retained within the case using a pillow block retainer design. The tube openings were machined over-size and aluminum shims are provided for an exact fit. The shim is a softer alloy than the mounting blocks. This combination provides adequate holding strength to secure the tube when maximum vibration levels are applied in each of the three plans.

A vibration mock-up was constructed to determine the vibration levels imposed on the tube with an input of $0.6 \text{ g}^2/\text{Hz}$ spectral density. The initial vibration isolators selected for this test were Robintech Series 7002. This isolator has an axial to lateral stiffness ratio of 5:1 and a nominal vertical frequency resonance of 9 Hz. The isolators were mounted to the bottom of the case and then assembled to the vibration fixture.

A vibration test was conducted using a simulated spectrometer and electronics mass. This arrangement placed the vertical center-of-gravity approximately 3.5 inches above the center of the isolator resilient material. A 10 g sinusoidal sweep was applied to the vibration table in a lateral plane. At this input level the isolator performance was normal and the transmissibility to the case was 0.13. A resonance near 178 Hz indicated a transmissibility of 3.1 from the case to the support structure. The equipment was then set up for random vibration. The random test was started at 19 db below $0.6 \text{ g}^2/\text{Hz}$ and brought to that level at the rate of 6 db per octave. At 3 db below the maximum level, the isolators were bottoming which created side slap. The tests were discontinued at that point.

Another survey of available isolators was made and the Barry Controls combination isolator was selected. This isolator provides protection from both vibration and shock inputs in a single unit that combines a vibration isolator with a high-deflection shock attenuator. Gussets were fabricated to mount the Mass Spectrometer such that the center-of-gravity was level with the top isolator flange.

A vibration test was again conducted during which no mechanical problems were encountered. The vibration level was brought up to $0.6 \text{ g}^2/\text{Hz}$ and run for six minutes duration in each plane.

IV. SYSTEM TESTS

Several tests have been performed on the mass spectrometer system to verify the performance specifications listed in Section II. In addition, a great deal of subsystem testing has been done to verify that design specifications have been met. These subsystem tests have been discussed in the design and development, Section III. Some performance specifications evolved from the applications study which were not included in those listed in Section II. To the extent time has permitted, tests have been run to evaluate these additional performance requirements.

4.1 ULTIMATE PRESSURE AND PRESSURE BUILD-UP RATE TESTING

During the development of this system it has been difficult to maintain an evacuated ruggedized mass spectrometer for very long periods of time. When the commercial tube was being tested the time available for bakeout was quite limited due to electronic testing. The testing on ultimate pressure and pressure build-up rate has been revealing but bakeout for longer periods will be necessary before final results can be determined.

The results of testing to date, however, have shown that after a tube is exposed to the atmosphere for some length of time, the pressure can be reduced by the primary pump and by the ion pump to 5×10^{-8} torr without a bakeout. If the pump is turned off, the pressure build-up rate is approximately 10^{-5} torr per minute. The build-up was the result of outgassing, not leakage.

After a bakeout of 150°C for about 38 hours the ruggedized monopole can then be closed off and the build-up rate in pressure has been observed to be about 10^{-7} torr/minute. The built in ion pump power supply can evacuate the system from 3×10^{-5} torr, which means that after 36 hours bakeout at 150°C the system could be closed off approximately 6 hours and restarted with the built-in pump supply.

The ultimate pressure which has been reached in the system has been 5×10^{-8} torr. This occurred after the ruggedized tube had been pumped without

bakeout and with no filament current. This system should be capable of an ultimate pressure of 10^{-8} torr with the filament on after a bakeout at 150°C for some time. (See Figure 20)

The system component which made it difficult to reach a low ultimate pressure was an oil contaminated primary pump. Due to rapid recycling during development testing, the trap in the primary pumping system was unable to remove all the oil which may have accumulated by back streaming from the mechanical pump. Some of this oil reached the spectrometer system and was retained. During the development testing it was not possible to bakeout for a long time and thus remove these hydrocarbons.

4.2 MASS RANGE

The performance specifications on this contract call for sweeping to 300 AMU. Due to the difficulty of sampling higher mass gases, two indirect methods have been used to prove that the maximum 300 AMU sweep has been attained.

The stability diagram, Figure B2 in the Appendix, was used to calculate the maximum range of mass;

Since;

$$q = \frac{4e V_{rf}}{m r_o^2 \omega^2}$$

$$\text{and } \frac{q}{a} = \frac{1}{2} \frac{V_{rf}}{V_{d.c.}}$$

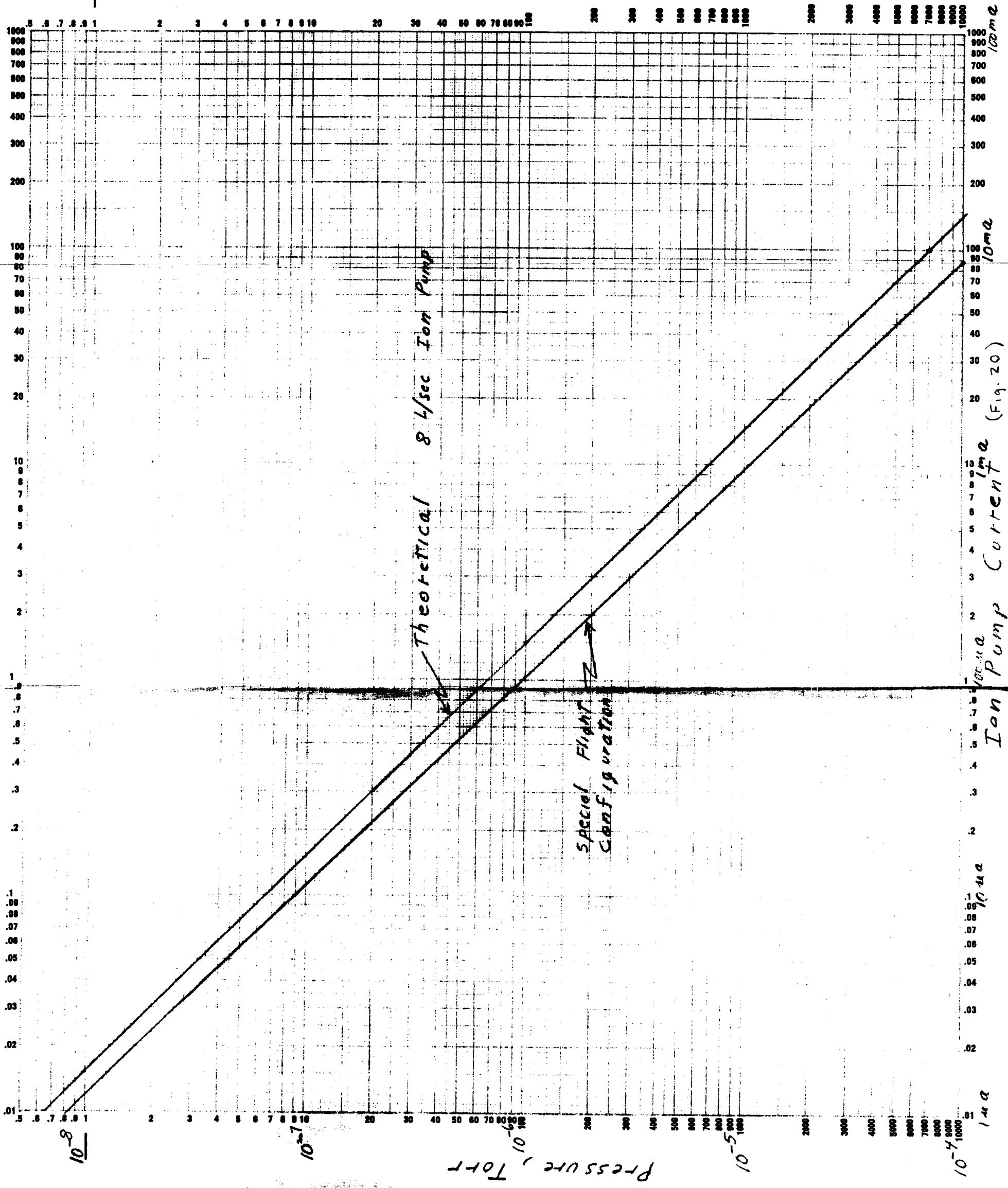
See Section III or Appendix "B" for notation.

Then substituting for the constants;

$$m = \frac{.186}{q} V_{rf}$$

where m has atomic mass units and V_{rf} is in volts

FOLDOUT FRAME



Unity resolution was attained with the appropriate ion source bias voltages, when $V_{rf} / V_{d.c.} = 11.1$

$$\text{or, } q/a = 5.55$$

When the slope is plotted on the stability diagram, Figure B2, the mass which is stable at the maximum V_{rf} varies depending on which point of the stability region is chosen. The maximum $V_{rf} = 650$ volts, and the range of q is 0.32 to 0.43.

From this range of stable values for q , the maximum mass range must be between 282AMU and 376 AMU.

In order to more accurately determine the range, freon was sampled. This gas gave peaks in the higher mass range. The spectrum was recorded and unit peak separation was observed to be constant with respect to time of sweep beyond mass 40. The time to reach the maximum sweep voltage was plotted and the range was measured to be 300 mass units. This value was then recorded on the mass range meter.

4.3 RESOLUTION

The voltage settings on this system have been adjusted to give unity mass resolution over the range from 1 - 300 AMU. Unity mass resolution is defined as 10% valley between two adjacent peaks. To test any two adjacent peaks for unity resolution, the height of the two unsaturated peaks were added. The sum was multiplied by 10% and this product is the maximum height of the overlap region between the peaks.

When the range is decreased and the sweep period is maintained at 60 seconds, the resolution can be shown to give less than a 10% valley between two adjacent peaks. The resolution at slower speeds is therefore better than the performance specifications called for.

4.4 LINEARITY

For a 60 second sweep, the linearity of the recording of a spectrum from 1 AMU to 300 AMU is about 1%. The device is not linear below 40 AMU because of the nonlinearity of the state-of-the-art clamping circuit diodes which are used in the sweep circuit. A graph of this region is shown in Figure 22. This deviation from linearity should be acceptable for automatic read-out circuitry since the sweep characteristics are repeatable from scan to scan.

4.5 VIBRATION TESTING

The purposes of the vibration testing were threefold. The operation of the unit during vibration was to be determined. The ability to withstand vibration was to be demonstrated; and finally, any vibration problems were to be diagnosed and corrected.

The test set-up for the vertical plane of vibration is shown in Figures 23, 24, and 25. Since the ion pumps for sustaining the vacuum have not been ruggedized, they were connected through a metal bellows tubing.

The tests which were run are listed in the following outline.

VIBRATION TESTS
FLIGHT MASS SPECTROMETER

FIRST TEST - LONGITUDINAL PLANE

1. Sine Wave Sweep

20 to 2000 cps in 2 to 3 minutes.

0.1" amplitude constant from 20 to 31 Hz.

10 g constant from 31 to 2000 Hz.

2. Random 0.6 g²/Hz, 20 to 2000 cps for six minutes.

SECOND TEST - LATERAL PLANE

1. Sine Wave Sweep

20 to 2000 cps in 2 to 3 minutes.

0.1" amplitude constant from 20 to 31 Hz.

10 g²/Hz, 20 to 2000 cps for six minutes.

THIRD TEST - VERTICAL PLANE

1. Sine Wave Sweep

20 to 2000 cps in 2 to 3 minutes.

0.1" amplitude constant from 20 to 31 Hz.

20 to 31 cps

10 g constant from 31 to 2000 Hz.

2. Random 0.6 g²/Hz, 20 to 2000 cps for six minutes.

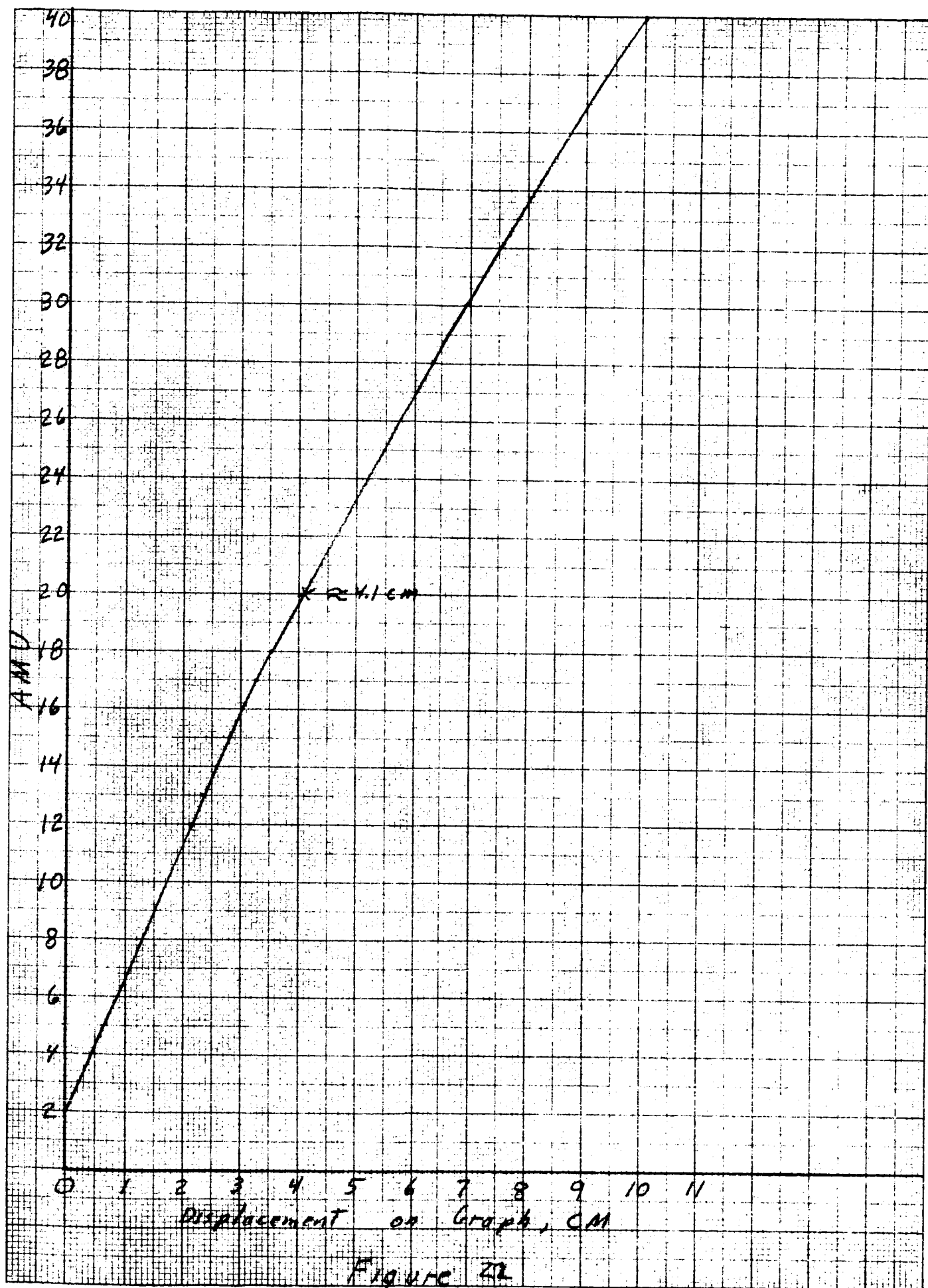
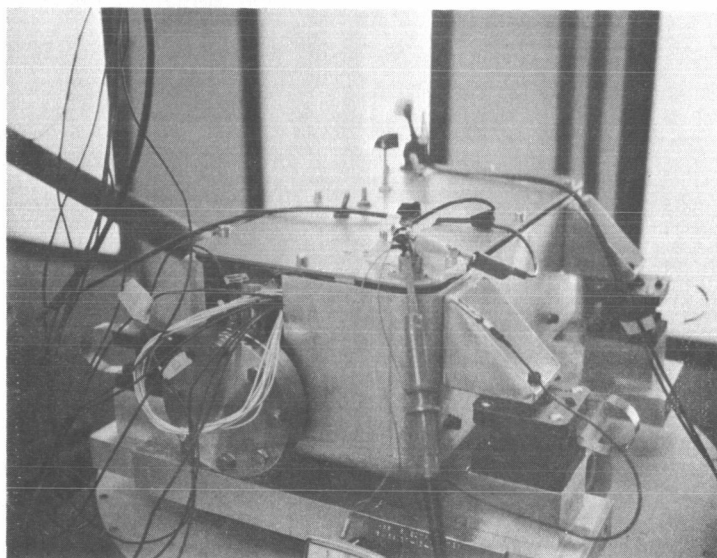
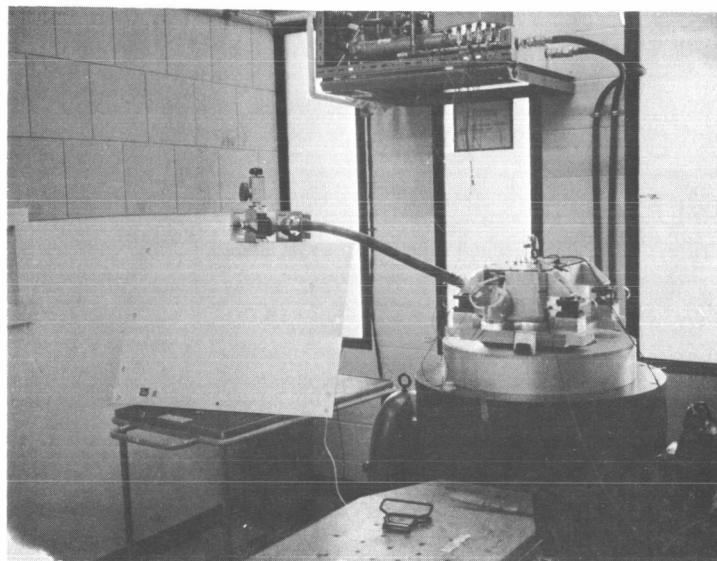


FIGURE 22



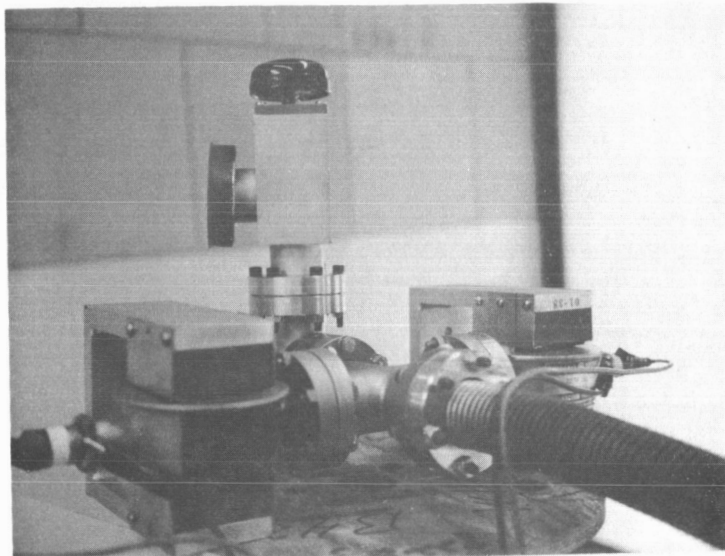
Vibration Tests of Mass Spectrometer System,
Unit on Vibration Stand

FIGURE 23



Vibration Tests of Mass Spectrometer System,
View of Flexible Hose

FIGURE 24



Vibration Tests of Mass Spectrometer System,
Ion Pump Arrangement

FIGURE 25

Since both spectrometers had been previously vibrated at Vacuum Products, only one spectrometer, with the split ceramic rod support, was vibrated in the systems test. This spectrometer has in fact been through much more vibration than was required by the performance specification on this contract.

The unit withstood vibration well. A decrease in sensitivity was noted which may have been as large as 10%, but it was not possible to achieve exactly the same exhaust and bakeout cycle before and after vibration, so the sensitivity may have been affected by a different bakeout time.

The unit operated with degraded accuracy during vibration because of peak noise. The baseline noise and scan seemed unaffected, however, so the presence or absence of gases could be monitored even during vibration.

It is recommended that the other spectrometer be vibration tested at the NASA Astrionics Laboratory. Prior to this a ruggedized oscillator crystal will be supplied by GE and added to the system in order to determine if the system electronics can be made to operate with a higher partial pressure accuracy during maximum vibration.

4.6 ADDITIONAL TESTING

A replacement of an electron multiplier was necessary in the spectrometer using the split ceramic rod support. This was probably caused by running the unit at an internal pressure which was too high.

In the second spectrometer, a reversed connection made during testing caused a failure also in the electron multiplier. Because of these two failures, it was not possible to perform various re-cycling tests including bakeout, exposure to different gases, and sampling at various pressures. The initial electron multiplier gain decreases rapidly when first put into use after which it becomes more stable. The effect of re-cycling tests would have been unresolvable from natural initial aging, and there was insufficient time to allow for this aging.

V. RECOMMENDATIONS AND CONCLUSIONS

This effort has successfully proved that a non-magnetic flight-type mass spectrometer can be produced as flight hardware using a monopole mass spectrometer. This mass spectrometer can be used in many applications of space flight.

In flight hardware, other environmental requirements must be met but none of the requirements are as stringent as the vibration requirements demonstrated by this feasibility model. No additional development type program would be necessary to show that the remaining requirements can be met. Further testing will, however, be necessary to determine the performance as related to the particular applications. This testing will be necessary to determine the extent of modifications necessary.

One area which does need some additional development effort is the ruggedizing of an ion pump. If time permits and if the application demands an ion pump, development in this area should be considered.

The only way to achieve a major decrease in weight and power in a mass spectrometer beyond what has been accomplished in this contract, is to develop the new and unique General Electric 3-D quadrupole design. The total power for the sweep circuit may be as low as 2 watts, and this in turn would reduce the weight of the electronics. The electronic design effort from this contract is directly applicable to the 3-D quadrupole mass spectrometer control circuitry. At the present stage, this 3-D quadrupole mass spectrometer has not yet progressed beyond the development stage. After the initial work is completed, its performance for flight applications can be evaluated.

Some modifications which could yield a better system for the monopole mass spectrometer flight hardware are considered in the following sections.

5.1 MASS SPECTROMETER MODIFICATIONS

Both of the flight monopoles are feasibility demonstration models. As such they differ in several ways from actual flight hardware. The most obvious difference is in the flanges. Were an actual piece of flight hardware to be built, the tubulation and flange provided for the laboratory exhaust system would be replaced by a pinch-off. The sustaining pump for flight hardware would be ruggedized and hence could be welded directly to the tubulation provided. This would eliminate a second pair of flanges. The 4-1/2" flange would be more difficult to eliminate, but it could be done by replacing the flange by a ring of smaller diameter and welding a thin cover plate including sampling system to the ring. Were these changes made, the weight of the flight monopole would be about 3.5 pounds.

Two minor changes should be made to allow for easier assembly. The threaded ion source support rods should be rotated about 45° relative to the end plate so that none of them interfere with the connections to the ionization gage header. It would also be wise to use a different material for pins in the header so that spot welds could be more readily made. After the results of further vibration tests, it should be possible to select one method of RF pole support as superior, but as of now, it is a matter of pure conjecture.

If the elimination of more weight from the tube is required, the best possibility appears to be by eliminating the inner envelope and the collar. The multiplier base could be removed and the multiplier mounted directly on its flange. The tubing for the vacuum jacket could be slit lengthwise and the analyzer-ion source assembly mounted directly on the lower part of the tubing by fastening the bottom of the "V" block directly to a clamp welded in the bottom of the tube. The ion source would not be changed. The advantage of this scheme is that vibration of the analyzer

ion source assembly would be held to a minimum. Since it is one assembly, it could be built up and tested in a standard tube envelope prior to assembly of the flight model. Thus the chance of obtaining a good tube with no costly rework and rewelding would be minimized. The analyzer to multiplier distance could be held to $\pm 1/16$ " which would be an acceptable tolerance for operation. The 4-1/2" flange or ring (as would be in flight hardware) could be eliminated entirely. It is conceivable that such a unit could weigh as little as 2.5 pounds. In such a model, it would be necessary to have good thermal contact between the V block and the vacuum jacket. Also both parts should be made of the same material to eliminate the problem of differing thermal expansion coefficients. To manufacture a flight monopole in this configuration would require time and money, whereas by eliminating the flanges from the feasibility model one could obtain flight hardware for little additional expense.

5.2 ELECTRONICS

The electronic control circuits could be used for flight applications except for minor modifications to meet additional environmental requirements (e.g. temperature range) if the present size, power, and weight are acceptable. Improvements in size and power could be gained by packaging in a modular form and increasing the efficiency of the power supply. Also, depending on the application, the power consumption could be reduced even further by reducing the mass scan range.

The temperature variations encountered in flight applications would require testing to determine the effects on the performance of the circuits. Where critical parameters are effected, modifications would be required to compensate for the variations. Tests were performed on the crystal oscillator and the power supply to determine temperature effects over a temperature range of -67°F to $+167^{\circ}\text{F}$ since these are two of the most critical circuits. The performance of the oscillator is given in Section 3.2.2.2, and exceeds the stability requirements over the temperature range required for most applications. The power supply variation with temperature was less than 1.5% over the temperature range. Most of the variation is due to the regulator and this can be improved with minor modifications. By using temperature compensated zener diodes as references both in the power supply and in the individual circuits where they are presently used the specifications outlined in Section III could be met with the present power supply design over the temperature range. The remainder of the circuits would have to be tested over the temperature range to determine their performance. However, components for and the design of these circuits were intended to meet flight temperature variation requirements and should require no major modifications to meet the specifications for flight hardware.

Other environmental requirements to be considered for a flight qualified unit are the humidity and reduced pressures of space flight. Provisions must be made to prevent arcing of the high voltages associated with this equipment (5000 VDC and 3000 VDC and etc.) in a reduced pressure and high humidity environment. Humidity will also effect the high impedance (10^{15}ohms)

insulation requirements at the input to the electrometer amplifier. Care in selection and sealing of connectors and module would eliminate these problems.

The power of the mass spectrometer electronics is largely used in the RF control circuits which determine the mass range to be scanned. The amount of power required is directly proportional to the mass range. The peak power required to sweep to 300 AMU is approximately 19 watts input for the RF section alone, and a total power requirement of 34.5 watts for the present equipment. To extend the sweep range to 600 AMU would require an increase in RF power (and therefore the total power requirement) of fifty-six watts. If, however, the mass range could be reduced for a particular application to 50 AMU the total power requirement would decrease to less than 20 watts.

There are other improvements that could be made in the performance of the electronics with increased circuit complexity. The power for the filament regulator could be supplied through a direct DC to DC conversion which would decrease the total power required by approximately 1.5 watts.

If a more linear sweep voltage is required, some modification of the RF rectifier portion of the scan control circuitry will be required. This would require a high speed high voltage diode to replace the seven used in this unit, but to date, a suitable diode is not available. Diode manufacturers indicate however that development is being done in this area which could result in a suitable device. If a device is not available, a more complex circuit could be employed to solve this problem.

5.3 PACKAGING MODIFICATIONS

Printed circuit boards were used in the feasibility model to provide rapid accessibility to the circuit components. Circuitry in a future flight qualified model should be packaged in a modular form that would permit a higher density package.

The aluminum shims used under the tube retainer clamp can be replaced with a machined asbestos shim for easier bakeout. The material should be hard and machinable so that the clamping properties of the aluminum are retained.

A heat jacket tailored to the tube and support hardware is available from Briscoe Manufacturing Company, P.O. Box 628, Columbus, Ohio 43216. The jacket could be a lace-on device which would provide convenience when compared with a heat jacket that requires wrapping.

The ion pump magnet and the outer jacket of the mass spectrometer tube would be a welded structure. The flanges would be eliminated on a flight qualified unit.

The electronics would be packaged in the contoured modules such that they would utilize the space around the tube. An estimate of the enclosure size for such a package would be 16" wide x 7" high x 7" deep.

APPENDIX A

FLIGHT MODEL MASS SPECTROMETER APPLICATIONS STUDY

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1.0 INTRODUCTION

An applications study was requested as a part of the NASA Contract NAS8-21217. This report presents the findings of the preliminary study. After this report is completed, the study will be continued with the objective of supplying details where needed and substantiating the findings of this report.

The study is necessary to consider the full extent of problems involved in converting a laboratory instrument to a piece of flight equipment. The usefulness of the information monitored by this equipment has been considered. The instrument parameters necessary for gathering this information in varied applications are specified.

1.1 CONTRACT REQUIREMENTS

The primary purposes of this study are to determine how a mass spectrometer system can be used in the interstage areas of Saturn missiles and to determine how the system could be used in the S-IVB workshop for hazards monitoring. On the basis of these findings the mass spectrometer system for each application is to be determined.

In order to determine the mass spectrometer system specifications, specific ambient parameters and operating procedures must be defined. For example, the ambient pressure profile helps to determine the sampling system. The sampling period helps to determine the control and readout circuitry. The range of scan helps to determine the average power consumption. The mission measurement requirements help to determine whether or not a magnetic leakage flux from an ion pump is permissible. The information content of monitoring mass numbers from 300 AMU to 600 AMU helps to determine the need for modifying the mass spectrometer to operate in this extended range.

1.2 NEED FOR THE STUDY

The need for this study can be seen by considering an example situation. If a large leak were to occur in the interstage and an explosion were to result

from the build-up of H_2 in this interstage area, it is possible that the force and temperature created would extend the deflagrations or explosion into the adjacent stages. An explosion having a 100% yield in the SIC stage would cause a pressure wave to be propagated toward the spacecraft area. If an abort were executed at the instant of such an explosion the launch escape module could not outrace this pressure wave. The shock wave would pass over the spacecraft with an overpressure sufficient to destroy the craft. Clearly, a signal to abort is needed which would occur a few seconds before an imminent explosion. In the present Saturn missiles no such signal is available during liftoff and flight.

A mass spectrometer is an instrument which has the potential of making the measurement for generating the signal described in the example above. However, a mass spectrometer is used in general as an investigating instrument in a scientific or engineering laboratory. When such an instrument is to be used as a remote monitor, the operating procedures and ambient parameters must be considered. Problems such as drift in calibration, variations in the content of the sampled gas, and variations in temperature and ambient pressure can, in general, be compensated in the lab. As a remote monitor, a mass spectrometer system must be designed and operated in such a manner that the calibration can be maintained. It must be operated to automatically compensate for large changes in the ambient pressure. It must be designed to be accurate over a wide range of temperatures.

The design of the system may vary for each specific application. Not all of these design features are to be incorporated in the feasibility model. It is necessary, however, to know how extensive any modifications to the feasibility model must be in order to design flight hardware. For some applications, the operating procedure and mass spectrometer system may have to be complex to perform the measurement required. It is necessary to decide whether the data is important enough to merit the effort of measurement. This determination leads to the final need for this study.

Can accurate data attained by the mass spectrometer system be used to accurately predict a hazardous situation or failure? In many cases the knowledge

that a leak or contaminant exists is not sufficient to predict what the effect of the phenomenon might be.

It may also be necessary to know the leak location or the quantity of the contaminant. The extent of information needed in each application has been considered.

1.3 SCOPE OF THE STUDY

The prime purpose of the contract is to show the feasibility of constructing a monopole mass spectrometer with certain environmental and operational guidelines. As a result, the amount of effort which can be devoted to this applications study is limited. In an effort to make the study as thorough as possible, it has therefore been necessary to rely upon the validity of related studies and in some cases extrapolate from these results.

A better approach would be to independently analyze the applications, check the validity by experiment and compare the results to related studies. Some thought should be given to performing an applications study with this approach after this preliminary study has been completed.

2.0 GENERAL REQUIREMENTS

The mass spectrometer is a versatile instrument used for detecting the presence of gases or vapors. The uses of such an instrument in the aerospace program are quite varied:⁽¹⁾

1. To determine the composition of the earth's upper atmosphere.
2. To monitor the composition of pilots' expired breath in high altitude aircraft for medical studies.
3. To determine residual gases in simulation chambers.
4. To analyze planetary atmospheres and surfaces.
5. To detect trace contaminants in space cabin and workshop atmospheres.
6. To detect rocket fuel leakage in flight and before launch.

Items 5 and 6 are of major interest in this study. Some of the major problems in using a mass spectrometer for those applications are considered in a

generic manner in this section.

2.1 MASS SPECTROMETER CALIBRATION & ACCURACY

Measuring the partial pressure of O_2 and H_2 accurately requires an instrument which can maintain calibration over the required time. A mass spectrometer requires periodic calibration, and the calibration must be considered as a necessary part of the operating procedure. The length of time that the unit will be able to maintain calibration must be considered in relation to the particular application. Some long term applications may require remote and automatic calibration. It may also be possible to compare data with another type of sensor for periodic calibration.

The regulation and accuracy requirements placed upon the electronic controls have been specified to maintain a calibration sufficient for a wide variety of applications. The major cause of drift is expected to result from chemical reactions on sensitive surfaces within the mass spectrometer tube.

2.2 ENVIRONMENT AND LOCATION

The environment in which the mass spectrometer must accurately operate extends over a large range. The most critical environment is vibration during launch. A major portion of this contract is devoted to designing the monopole mass spectrometer for operation in this vibration environment.

The ambient pressure range will vary from approximately 7.6×10^2 torr to 10^{-8} torr for all applications. In some applications, a variable sampling orifice may be required, since the pressure within the mass spectrometer should be maintained within the range of 10^{-6} torr to 10^{-8} torr.

The temperature range will be different for each application. The effect of temperature excursion on the monopole mass spectrometer has been considered throughout the design phase of this contract. In particular, most electronic components have been selected to operate over a wide range of temperatures. However, some modifications and extensive testing will be necessary to assure that flight hardware instrumentation will be acceptable throughout the

temperature range encountered in each particular application.

Since the primary application location is the interior of missiles and spacecraft, size, weight and power requirements are critical. The monopole mass spectrometer is particularly suited to these requirements. A major part of the contract is devoted to a redesign of the electronic controls for more efficient operation and therefore lower power consumption. The absence of a magnet in the mass spectrometer not only reduces weight but helps make the spectrometer compatible with scientific payloads containing magnetometers. The ion pump which is a part of the system used for sustaining a low pressure in the mass spectrometer contains a magnet. The presence of this magnet will be evaluated in relation to the applications.

Another critical environmental factor is the nature of the sampled gas. For example, sampled water vapor tends to be cumulative. One of the chief reasons for bakeout in high vacuum systems is to drive off the water adsorbed on the metallic parts. This same reason holds true in a mass spectrometer. In addition, H_2O tends to decrease the gain of the electron multiplier. Other gases also affect the multiplier gain. Oxygen tends to change the surface characteristics of the first multiplier dynode after O_2 is sampled for some time. The gain of the multiplier decreases during this time but then becomes stable. This behavior places constraints upon operating parameters such as scan time and single peak monitoring, if partial pressure measurement accuracy is to be maintained.

Another category of gases which may seriously affect the electron multiplier is the highly reactive oxidizers. This is a problem which has been observed in ground mass spectrometer applications (2)

Nitrogen

tetroxide, N_2O_4 , is a toxic liquid used as a hypergolic propellant. When an electron multiplier was used in the presence of N_2O_4 , the multiplier was damaged. The data on the effects of N_2O_4 is very limited. Testing will be necessary to evaluate the problem.

2.3 DATA OUTPUT AND INTERPRETATION

In the laboratory the output signal or spectrum from the mass spectrometer

is generally recorded on a graph and the data is manually reduced to determine partial pressure and mass number of the sampled gases. It is also possible to monitor a particular gas by recording the peak corresponding to that mass versus time. In general, the output for a particular application will be a variation or combination of scanning the spectrum or monitoring the partial pressure of a particular gas.

In general, data from the interstage areas of Saturn missiles during flight is transmitted through telemetry to ground. Mass spectrometer scans could also be transmitted through the telemetry system on a subcarrier in analog form or an intermediate A to D conversion may be desired. The data could be reduced manually or automatically on the ground. Automatic data reduction will require greater stability of the instrument, storage of calibration parameters in the computer, and data reduction.

In some programming applications a display may be required in the spacecraft or workshop. Onboard data processing may be necessary in this case. If the mass spectrometer were to be used as a sensor in an automatic abort system, onboard data processing would be required in the missile.

In each application the desired mode of readout must be considered with respect to the required accuracy and purpose of measurement. Tradeoffs will be necessary to attain the optimum system.

3.0 INTERSTAGE SAMPLING

The specific measurements for which the monopole mass spectrometer system might be used will be discussed in this following section. The use of the mass spectrometer in the interstage areas will be considered only in those interstage areas bounding stages of the Saturn missiles.

3.1 DEFINITION OF INTERSTAGE AREAS

The interstage and skirt areas of the Saturn 1B and Saturn V missiles are the crosshatched areas shown in Figure A1.⁽³⁾ There are two separate interstage and skirt volumes in the Saturn V missile.

Cutaway views of the interstage areas of the Saturn 1B are shown in Figure A2.⁽³⁾ Typical experiment locations are shown as black boxes. In addition, some specifications are given for each zone or location in the adjoining Table of Figure 2. Similar information is given in Figure A3 for the Saturn V.⁽³⁾ The open volume between the tanks of the SIC stage of the Saturn V is also shown on Figure A3.

3.2 HYDROGEN AND OXYGEN MONITORING

The interstage atmospheres of the Saturn missile are monitored to detect any build-up of oxygen or hydrogen before launch. A build-up of a sufficient level of hydrogen and oxygen within the interstage volume presents an explosion hazard. In general, when both the oxygen and hydrogen reach the 4% level, an intimate mixture of these gases at atmospheric pressure can explode if the proper ignition source is present.

The tanks and propulsion systems are well designed and tested for structural integrity under pressures greater than the normal operating pressure.⁽⁴⁾ In addition, there are design specifications which state the maximum allowable gas leakage from the tanks and propulsion systems.⁽⁵⁾ Nevertheless, it is possible to have a failure which might cause a build-up of hydrogen and oxygen. There are hydrogen and oxygen propellant lines, valves and pumps located in each interstage area. In addition, the tank bulkheads form the upper and lower partitions in most interstage areas. A schematic representative of the areas is shown in Figure A4.⁽⁶⁾

The probability of failure in any structure containing H_2 or O_2 is difficult to predict. At present, the pre-launch build-up due to failure in a component or structure, is minimized by purging the interstage areas with N_2 gas. In order for H_2 and O_2 to reach explosion limits, leaks of both must occur which are sufficient to provide a 4% O_2 -- 4% H_2 atmosphere. The O_2 may enter the volume from the ambient atmosphere as well as from a leak. A graph showing the explosive limits of an H_2 , O_2 , N_2 mixture is shown in Figure A6.⁽⁶⁾

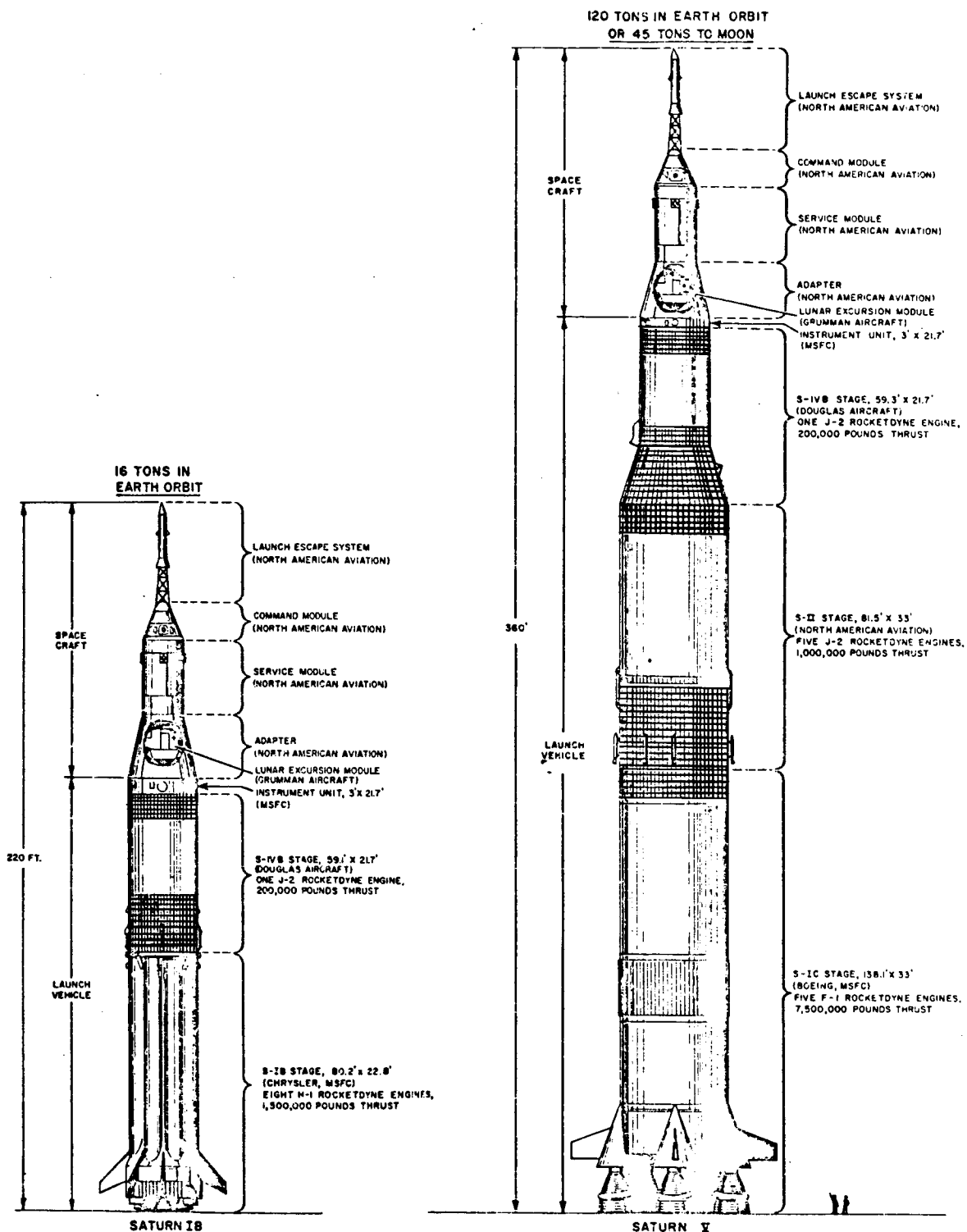


Figure A1. Saturn IB and Saturn V Configuration

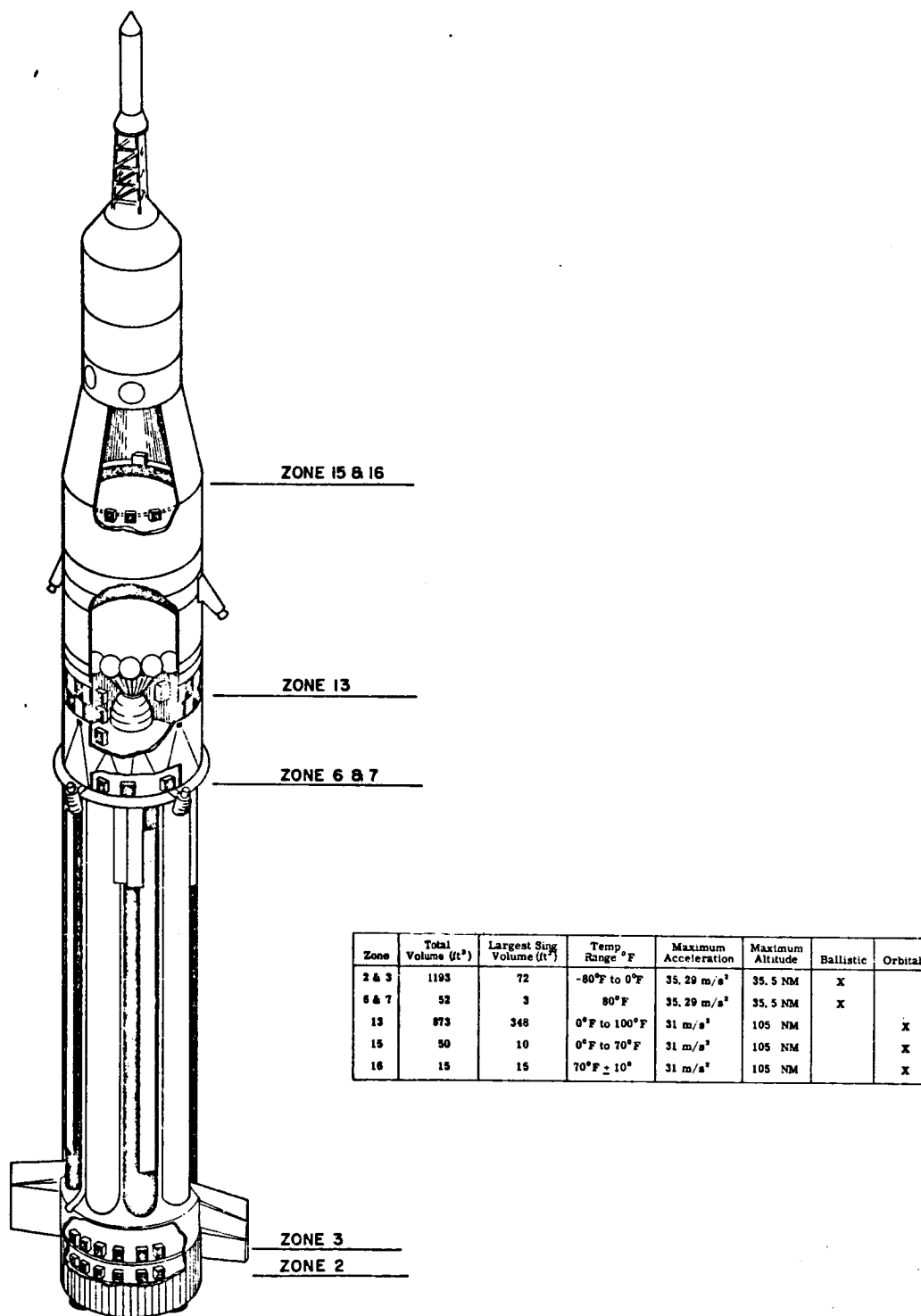


Figure A2. Saturn IB Launch Vehicle, Experiment Locations

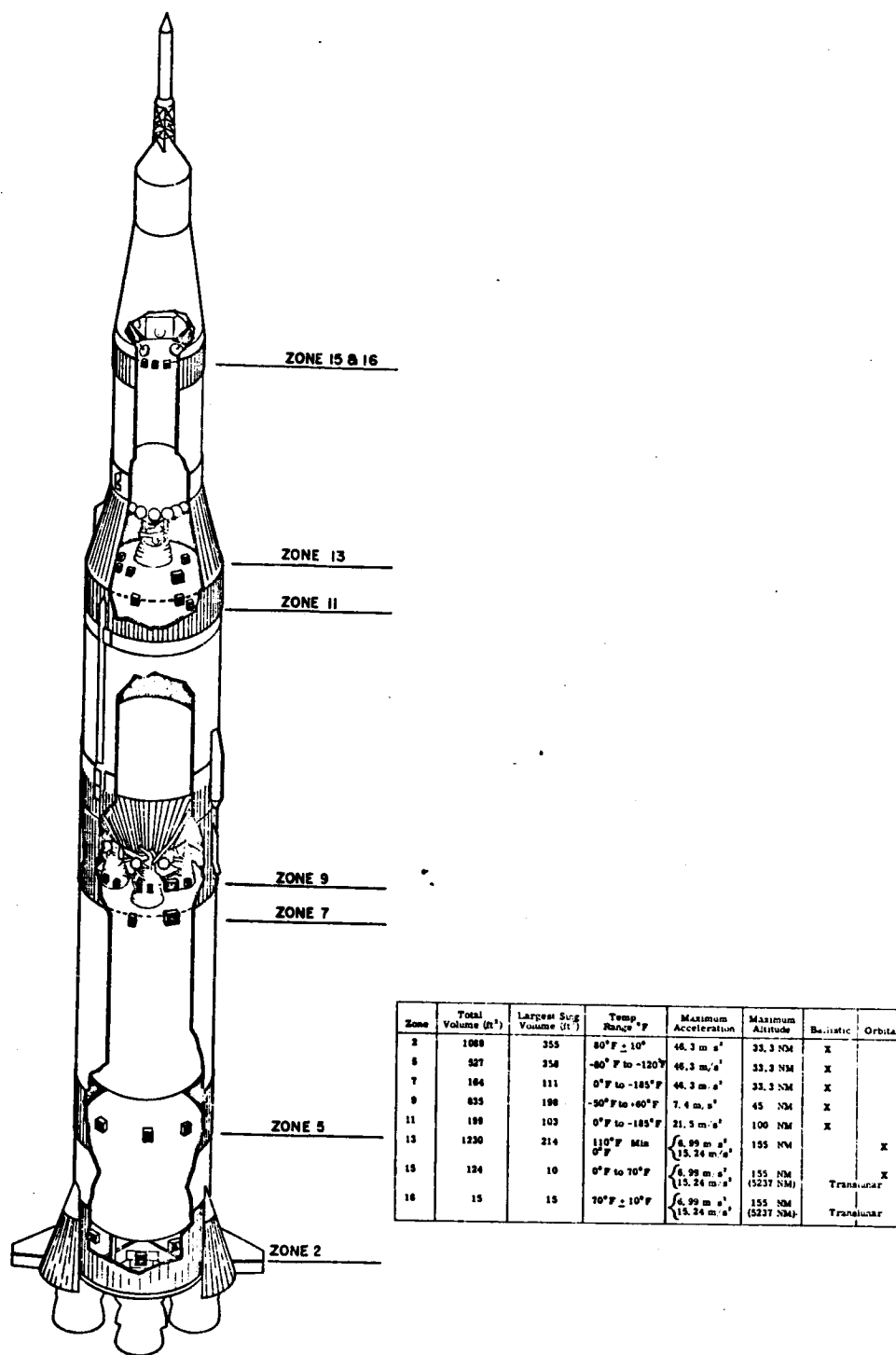


Figure A3 Saturn V Launch Vehicle, Experiment Locations

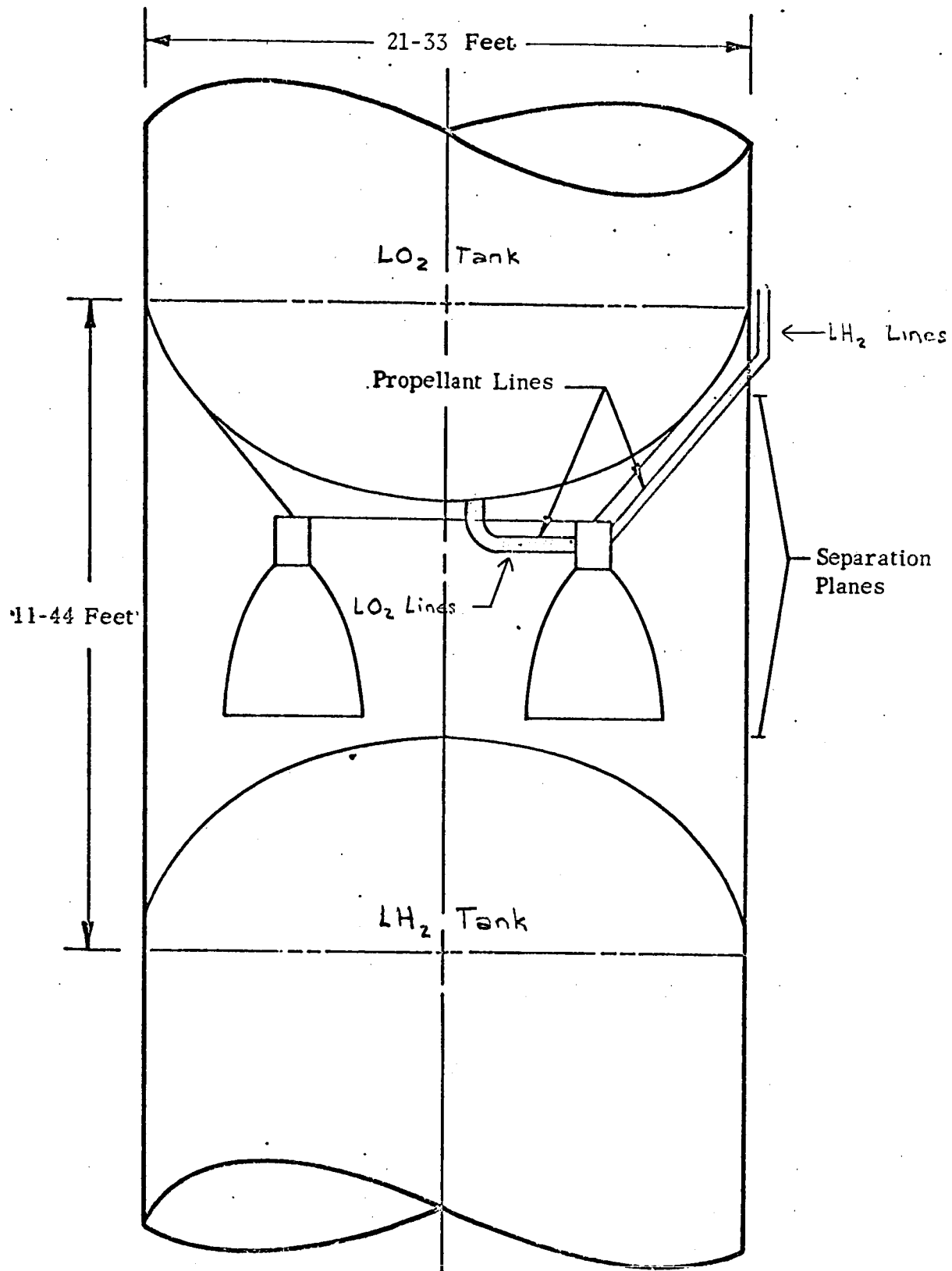


FIGURE A4 GENERAL CONFIGURATION OF INTERSTAGE

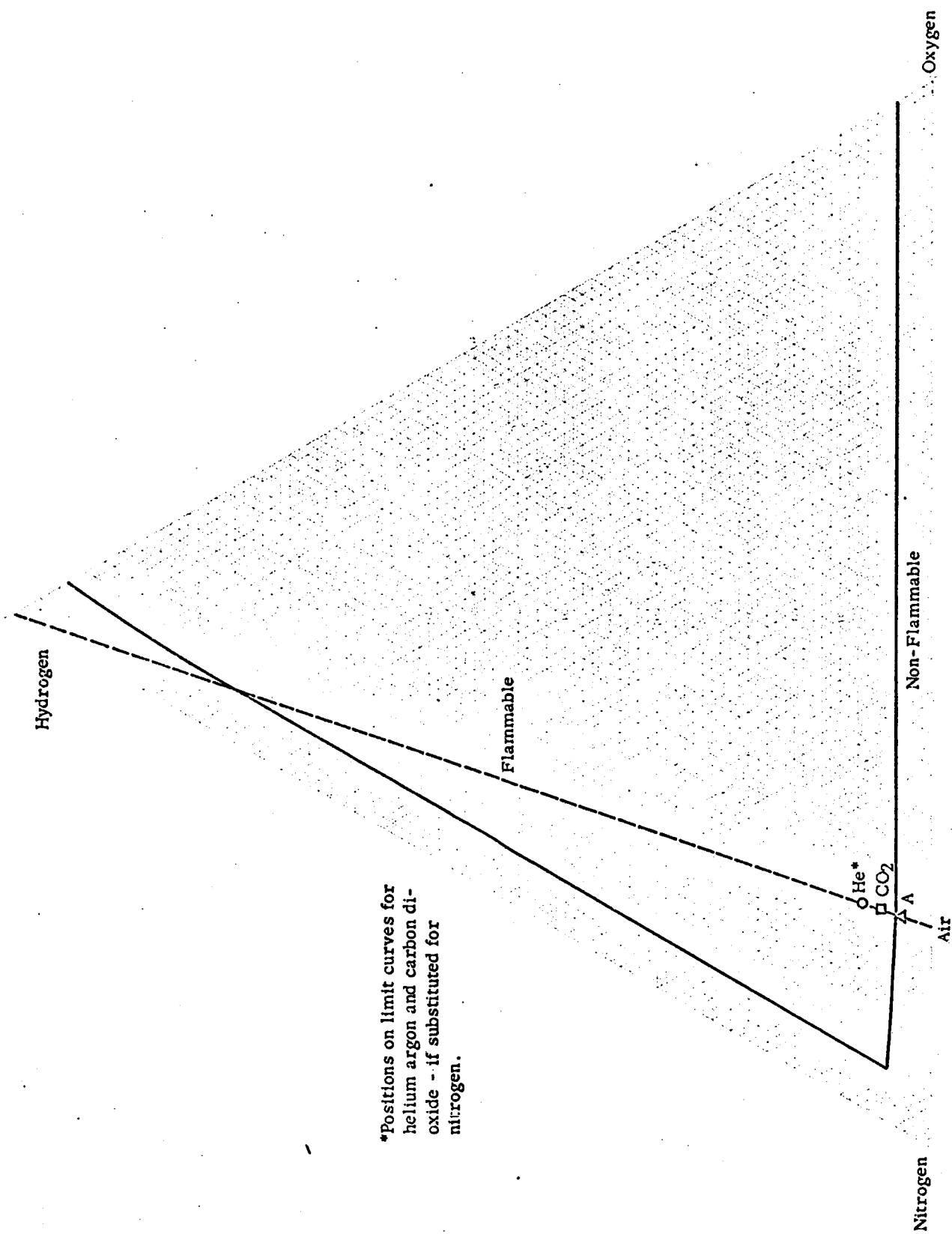


Figure A5 Flammability Concentration Limits

Studies have been performed to determine the specifications for the N_2 purge system. The system is designed to minimize the risk without hinder-normal pre-launch operations. Danger may arise, however, if the purge system fails. Since the purge system is disconnected before lift-off, danger may also arise during the remainder of the mission.

3.2.1 Critical Periods

The purge system must be operating prior to the LH_2 tanking for thirty minutes. If tanking has begun, and the N_2 purge system fails, the interstage volume would probably contain 99.9% N_2 .⁽⁵⁾ O_2 would begin entering the interstage through the exhaust ports and leakage areas from the outside atmosphere. Also, leakage from the propulsion system components would begin to build up within the volume.

The design limits on allowable leakage from the propulsion system is of the same order of magnitude for both hydrogen and oxygen.⁽⁵⁾ It is probable, therefore, that when the H_2 has reached the 4% level, the O_2 content will be sufficient to support combustion.

A similar situation occurs at liftoff. The N_2 purge system has been operating before the liftoff, so the interstage volume will be close to 99.9% N_2 . As the missile leaves the ground, mixing through the exhaust ports and leakage areas is increased due to the movement of the missile through the atmosphere. As the atmospheric pressure decreases with altitude, the interstage pressure will correspondingly decrease. Normal leakage from the propulsion system components would be expected to vary only slightly upon increasing altitude. Constant H_2 leakage into an interstage with decreasing pressure would cause an increasing percentage of H_2 . Even though the percentage would increase, the atmosphere may not support combustion at the higher altitudes.

Figure A6 shows the ignition curves for various percentages of O_2 and H_2 at low pressures.⁽⁶⁾ The pressure below which a gaseous $H_2 - O_2$ fire could not be sustained is generally accepted as .15 p.s.a., as shown by the dotted line on the graph. The altitude at which the atmospheric pressure drops

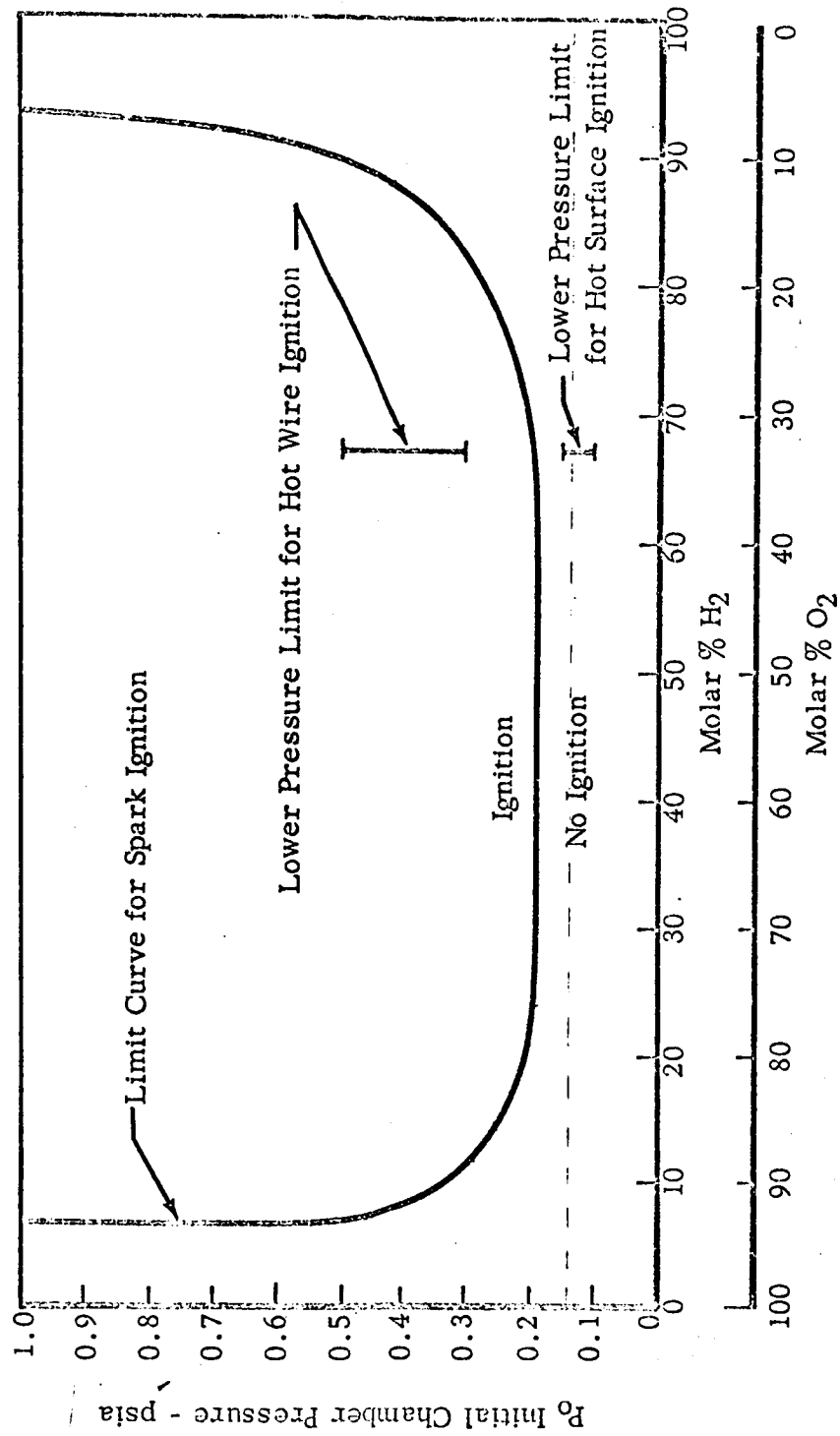


Figure A6 Flammability Pressure Limits

below .15 psia is approximately twenty nautical miles.⁽⁷⁾ The events which take place before this altitude is reached can be seen from Figure A7. Typical trajectories of the SIB and SV are shown.^(8,9,10,11)

The pressure drops below .15 psi before staging begins and within approximately two minutes from lift-off. The critical period for the build-up and initiation of gaseous H₂ and O₂ explosions starts after tanking begins and extends to the first two minutes after liftoff in Saturn flights.

3.2.2 Sampling Orifice and Amplification

The sampling system for the mass spectrometer during this phase can now be considered. For correct operation, the mass spectrometer should have internal pressure below 10⁻⁶ torr. If the ambient is 100% N₂, and the pressure is one atmosphere, the output voltage which is proportional to the partial pressure should be approximately full scale on the N₂ peak. At a sensitivity of 10 ampere/torr from the electron multiplier, for nitrogen, the current into the output amplifier is then 10⁻⁵ amperes. This current gives maximum output, IOV, for the lowest amplifier gain in the present feasibility model. As the ambient pressure reduces from 14.7 psi to 0.15 psi, the pressure in the tube reduces by two magnitudes to 10⁻⁸ torr, if the size of the sampling orifice remains constant. Now, if the output amplifier gain were unchanged, and if nitrogen were still the major constituent, the output voltage of the N₂ peak would be 0.1 volt, but if the gain were increased by 100, the output would again be 10 volts.

Now consider the possible H₂ and O₂ reading during this phase. Since 4% of both constitute a potentially explosive atmosphere, the accurate detection of H₂ and O₂ in the 1% range is desired. If the N₂ peak is at approximately 10V, the H₂ peak at 1% would be on the order of 0.1 volts. If the combined pressure decreases to 0.15 psi, a 1% H₂ peak would be on the order of .001 volts or 1 millivolt. An accurate reading cannot be made on this scale; therefore, scale switching or log amplification is necessary during this phase.

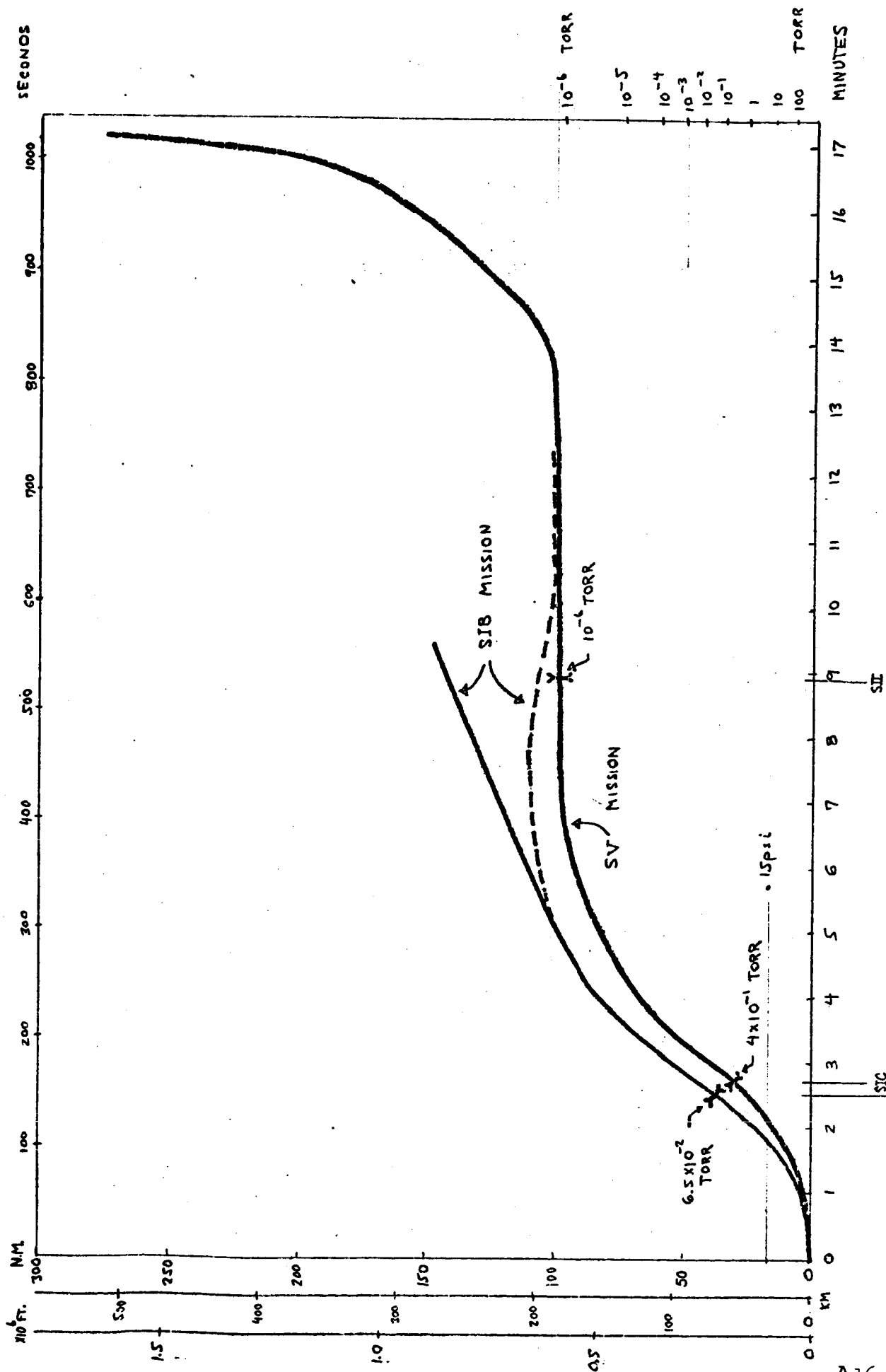


FIGURE A7 - SIB and SV Trajectories

The current for a 1% H₂ peak at one atmosphere ambient would be 10⁻⁷ amperes. As the ambient pressure decreases to 0.15 psi, the current from a 1% H₂ peak would be 10⁻⁹ amperes. The log amplifier would then be required to span approximately five decades to cover the range without requiring switching during the first phase of flight.

In summary, explosions resulting from the build-up of H₂ and O₂ gas in the interstage of Saturn-type vehicles could occur during the time interval after tanking to the first two minutes of flight. It would be advisable to use a constant size sampling orifice for the mass spectrometer system during this time. The inside pressure of the mass spectrometer could be maintained within a two decade range and a periodic gain increase or log amplification would give an output voltage which could be monitored.

Two important system specifications have now been determined; the number of sampling orifices and the output amplification. The need for only one orifice size for monitoring H₂ and O₂ before launch and during lift-off simplifies the system. Log amplification would be a desirable alternative since the system would be simplified by requiring no pre-programmed switching.

3.2.3 Scan Mode

Another important parameter to consider is the scan mode. The feasibility model is being designed with a repetitive scan from 1 to 300 AMU and a manual scan. Clearly this is not mandatory for the application of monitoring O₂ and H₂ partial pressures in the interstage. It would seem that the most straight forward method of monitoring would be alternating readouts of the H₂ and O₂ peaks and possibly the N₂ peak.

Monitoring the N₂ peak would indicate the efficiency of the purging system and is considered desirable. The monitoring of three peaks as compared to two would not add any significant scan circuit complexity.

The voltage regulation must be extremely critical if the spectrometer is to monitor a single peak, and for this reason the circuit complexity increases. A peak searching control must be added if discrete peaks are to be monitored.

For this reason, a linear scan is preferable. Of course, a linear scan will produce a spectrum, and the job of determining a specific peak reading would be transferred to the ground data management system. A linear scan will also give a record of other gases which may be advantageous. The scan would be required to range from H_2 at 2 AMU, to O_2 at 32 AMU. This would also include singly-ionized N_2 at 28, and doubly ionized N_2 at 14 AMU.

There is another advantage for continuous scanning. The gain of the electron multiplier will be less susceptible to change. As mentioned previously, the gain of electron multipliers change upon long exposures to high O_2 or H_2O concentrations. Any change in the gain changes the calibration and therefore the accuracy of the partial pressure measurement.

3.2.4 Accuracy - Partial Pressure Reading

The accuracy of the partial pressure reading and the AMU reading is important in many applications. In this case, the partial pressure for H_2 and O_2 should be determined accurately in the 1% range. If a constant H_2 leak should occur, the average build-up of H_2 in the interstage would increase at some predictable rate. This rate could be used to estimate the time necessary to reach a four percent average concentration of H_2 .

With a constant leak, and no H_2 escaping from the interstage, the build-up rate would be linear. Assume that the rate of build-up were to be determined during the interval from 1% to 2% H_2 . The rate would be, r ;

$$r = \frac{2\% - 1\%}{t_{2\%} - t_{1\%}} \quad \text{where } t_{1\%} \text{ and } t_{2\%} \text{ are the}$$

$$= \frac{1\%}{t_{2\%} - t_{1\%}} \quad \text{times when the average concentration reaches 1\% and 2\%.$$

If the accuracy of the determination of the percentage of H_2 is $\pm p$, then the worst case error would occur if

$$r_M = \frac{(2\% - p) - (1\% + p)}{t_{2\%} - t_{1\%}} = r_A - \frac{2p}{t_{2\%} - t_{1\%}}$$

where r_M = measured rate

r_A = actual rate

the actual time remaining before reaching the 4% level would be T_A ;

$$T_A = \frac{4\% - 2\%}{r_A} = 2(t_{2\%} - t_{1\%})$$

The time estimated from the rate measurement however would be, T_M ;

$$T_M \approx 2(t_{2\%} + t_{1\%}) + 4p(t_{2\%} - t_{1\%})$$

The percentage error in predicted time is therefore approximately 2p. If the error in H_2 measurement were allowed to be $\pm 10\%$, the worst case error in the predicted time for reaching the 4% level would in this case be 20%.

The build-up rate considered can be only an approximation because of the non-homogeneity of the hydrogen distribution which occurs during a leak. Furthermore, a four percent or greater hydrogen concentration does not indicate that an explosion is imminent unless both an initiation source is present and the oxygen level has reached four percent or greater. For these two reasons a $\pm 10\%$ accuracy on the partial pressure reading is considered adequate.

3.2.5 Average Concentrations and Gaseous Plumes

One of the most important and most difficult problems which has been considered in this study is describing the nature of the build-up of H_2 in an interstage. A most desirable description would be H_2 concentration profiles plotted against time and spatial coordinates. An important parameter for determining such a profile is the nature of the leak. In addition, knowing the probability for the occurrence of different types of leaks during various phases of the launch and flight would be desirable. Finally, the location of these probable leaks would complete the description.

Several studies^(5,6,13) have been performed which give preliminary descriptions of the H_2 concentration which might occur in the interstage areas. The extent and findings of these studies will be reviewed because the description of the concentration profile is important in specifying the number of

mass spectrometers, the location of each, the number of sampling orifices and the location of each. Since the studies of H_2 concentration give only a preliminary description, the conclusions derived from these studies must be considered preliminary, and indeed, only approximate.

In the first report⁽⁵⁾ the S-IVB aft interstage was selected for analysis of the leakage phenomenon. Three periods were considered:

1. Normal gaseous N_2 purge
2. Loss of purge after tanking has begun
3. Lift-off to 200,000 feet (approx. 30 n. miles)

During purge it was assumed that there was a homogeneous mixing of purge gas and leakage gas after several minutes and therefore the concentration of leakage gas was equal to the rate of leakage divided by the rate of purge gas. The high nominal H_2 leakage rate of the J2 engine and associated components is given as 1500 standard cubic inches per minute. The N_2 purge rate is given as 3820 standard cubic feet per minute. The concentration is given then as:

$$\frac{1500 \text{ in}^3}{3820 \text{ ft}^3} \times \frac{1 \text{ ft}^3}{1728 \text{ in}^3} \times 100\% = .023\%$$

Therefore no hazard exists. The leak rate, q_H , at which the average concentration would reach 4% H_2 could be calculated as:

$$\frac{q_H}{3820 \text{ ft}^3/\text{min}} \times 100\% = 4\%$$

$$q_H = 153 \text{ ft}^3/\text{minute}.$$

Another report⁽⁶⁾ indicates that the maximum leak rate of H_2 which could occur in the J2 engine area would be caused by failure of the transfer line, fitting or other component, allowing a full discharge of the propellants from the engine chill down circulation stage. For the J2 engine this amount would be 1.2 lbs/second.

When the liquid hydrogen from the leak is exposed to the gaseous nitrogen the hydrogen will be warmed and will change to a gaseous state. Therefore,

using the value for the density of hydrogen, ρ_H , at 0°C

$$\rho_H = .0056 \frac{\text{lbs}}{\text{ft}^3}$$

A leak rate of 1.2 lbs/sec. would therefore be equivalent to;

$$q_H = \frac{1.2 \text{ lbs}}{\text{sec.}} \times \frac{1}{.0056 \frac{\text{lbs}}{\text{ft}^3}} \times \frac{60 \text{ sec}}{\text{min.}}$$

$$q_H = 1.3 \times 10^4 \text{ ft}^3/\text{min} = 2.25 \times 10^7 \frac{\text{in}^3}{\text{min.}}$$

The average concentration of H_2 , C_H , for a 1.2 lb/sec. leak rate would be approximately:

$$C_H = \frac{q_H}{q_H + q_N} \times 100\%$$

where

q_H = Hydrogen leak rate

q_N = Nitrogen leak rate

Therefore

$$C_H = 82\%.$$

The next period considered was loss of purge after tanking has begun. The report⁽⁵⁾ points out that the purge operation begins thirty minutes prior to tanking and therefore the interstage would have $C_N = 99.95\%$. Now, if the purge system were to fail, the build-up of H_2 in a sealed interstage would be:⁽⁵⁾

$$C_H = \frac{q_H t}{V}$$

where t = time

V = interstage volume

or the time required to reach a given concentration would be

$$t = \frac{C_H V}{q_H}$$

With a high nominal leak rate of $1500 \frac{\text{in}^3}{\text{min}}$ and the S-IVB aft interstage volume of $14.4 \times 10^6 \text{ in}^3$ the H_2 concentration of 4% would occur in

$$t = \frac{(.04)(14.4) \times 10^6 \text{ in}^3}{1500 \text{ in}^3/\text{min}} = 383 \text{ min.}$$

or

$$t = 6.4 \text{ hours.}$$

Using the catastrophic leak rate of $1.2 \text{ lbs/sec.} = 2.25 \times 10^7 \frac{\text{in}^3}{\text{min}}$

$$t = \frac{(.04)(14.4) \times 10^6 \text{ in}^3}{2.25 \times 10^7 \text{ in}^3/\text{min}} = 2.55 \times 10^{-2} \text{ min.}$$

$$t = 1.5 \text{ seconds.}$$

In summary, the average concentrations of 4% H_2 might occur within the range of 1.5 seconds to 6.4 hours in the aft interstage of the S-IVB if the nitrogen purge were lost and a leak were present.

The third period considered in the report,⁽⁵⁾ was the time from liftoff to 120,000 feet or approximately 20 nautical miles. As stated before, this is the altitude above which the pressure is not sufficient for a $\text{H}_2 - \text{O}_2$ deflagration. The time required to reach 20 nautical miles is approximately two minutes. (See Figure A7). No purging occurs during this time since the purge system is disconnected at launch. The leak rate required to achieve a 4% concentration at that altitude is given as $3000 \text{ in}^3/\text{minute}$.

Checking this calculation,

$$Y_H^o = q_H t \quad \text{where } Y_H^o = \text{quantity of } \text{H}_2 \text{ gas at standard conditions}$$

$$C_H = \frac{Y_H}{Y_N + Y_H} \approx \frac{Y_H}{Y_N} \quad \text{where } Y_N = \text{quantity of } \text{N}_2 \text{ gas}$$

Since the interstage volume is $14.4 \times 10^6 \text{ in}^3$, the amount of H_2 for a 4% concentration is $Y_H \approx C_H Y_N$

$$= (.04)(14.4) \times 10^6 \text{ in}^3$$

$$= 5.8 \times 10^5 \text{ in}^3.$$

This volume of gas at .15 psi would be, neglecting temperature effects, $5.9 \times 10^3 \text{ in}^3$ at one atmosphere (14.7 psi). (The quantity of N_2 gas also decreases since the pressure is equalized by flow through the interstage vents as the altitude increases and the ambient pressure decreases).

Since
$$q_H = \frac{Y^o_H}{t}$$

Then
$$q_H = 3000 \text{ in}^3/\text{min} \text{ at standard conditions.}$$

In this calculation it was assumed that no H_2 was lost, but the amount of N_2 lost overboard was about 99%. Clearly this is a worst case calculation. Practically, the H_2 would also be lost through the vents in the interstage. It was stated that the leak rate would increase with a decreasing ambient pressure, therefore, the H_2 lost overboard would be compensated for. This is unlikely because the leak rate would not increase by a large factor.

The validity of this last calculation is important because a leak rate of $3000 \frac{\text{in}^3}{\text{min}}$ would give a concentration of

$$\frac{q_H}{q_N} = \frac{3000}{3820} \times 1728 = .046\%$$

during N_2 purge prior to launch. This concentration is about 5 parts in 10,000. The mass spectrometer system monitoring 5 parts in 10,000 would be expected to sense a peak change of approximately 5 millivolts on the low gain amplifier scale. This is a demanding requirement and the need for such a measurement has not been conclusively shown because of the previous assumptions. Clearly then, there is a need for a more accurate H_2 build-up model.

Instead of considering that all H_2 is retained in the volume, consider that the average concentration is given by

$$C_H = \frac{(q_H \text{ in} - q_H \text{ out}) t}{V}$$

where

$$q_H \text{ in} = \text{peak rate of } \text{H}_2 \text{ at standard condition}$$

$q_{H \text{ out}}$ = rate of H_2 lost through purge vents

V = interstage volume.

The concentration at any time can be calculated if $q_{H \text{ out}}$ is known. For purposes of illustration, the case for a constant one atmosphere pressure will be considered first. The rate of flow through the exhaust vents can then be assumed to be sufficient to equalize the pressure across the orifice so

$$q_{H \text{ in}} = Q_{\text{out}}$$

where Q_{out} is the total flow of all gases through the exhaust port.

The flow of H_2 through the exhaust port can be expressed if the H_2 is considered to be distributed homogeneously after some short time. The flow of H_2 through the exhaust port will then be proportional to the homogeneous concentration of H_2 in the interstage or

$$C_H = K q_{H \text{ out}}$$

where K is a constant of proportionality.

Since we recall

$$C_H = \frac{(q_{H \text{ in}} - q_{H \text{ out}}) t}{V}$$

then
$$\frac{(q_{H \text{ in}} - q_{H \text{ out}}) t}{V} = K q_{H \text{ out}}.$$

After some long time, considering that only H_2 is leaking into the interstage, the concentration of hydrogen will be equal to unity therefore,

$$C_H = 1 = K q_{H \text{ out}} \quad \text{for } t \rightarrow \infty$$

Also, since the pressure will be equalized for all time,

$$q_{H \text{ in}} = q_{H \text{ out}} \quad \text{for } t \rightarrow \infty$$

or

$$q_{H \text{ out}} / q_{H \text{ in}} = 1$$

from the previous equation

$$q_{H \text{ out}} K = 1$$

therefore

$$K = \frac{1}{q_{H \text{ in}}}$$

The flow of hydrogen through the exhaust port after substitution for K becomes

$$\frac{(q_{H \text{ in}} - q_{H \text{ out}}) t}{V} = \frac{q_{H \text{ out}}}{q_{H \text{ in}}}$$

$$q_{H \text{ out}} \left[\frac{1}{q_{H \text{ in}}} - \frac{t}{V} \right] = \frac{q_{H \text{ in}} t}{V}$$

$$q_{H \text{ out}} = \frac{q_{H \text{ in}}}{1 + \frac{V}{q_{H \text{ in}} t}}$$

Recalling that the equation for concentration is

$$C_H = \frac{(q_{H \text{ in}} - q_{H \text{ out}}) t}{V}$$

and substituting for $q_{H \text{ out}}$ results in

$$C_H = \frac{q_{H \text{ in}} t}{V} \left[1 - \left(1 + \frac{V}{q_{H \text{ in}} t} \right)^{-1} \right]$$

$$C_H = \frac{\frac{q_{H \text{ in}} t}{V}}{1 + \frac{V}{q_{H \text{ in}} t}}$$

Let

$$x = \frac{q_{H \text{ in}} t}{V}$$

Then
$$C_H = \frac{x}{1+x}$$

Recalling from Page 21 the concentration of H_2 was given by the expression

$$C_H = \frac{q_{H \text{ in}} t}{V} = x$$

for a sealed interstage. For $x = .04$ the two expressions evaluate to

$$x = .04 \text{ and } \frac{x}{1+x} = .0384$$

For low concentrations of H_2 the difference between the two expressions is slight.

Now it is possible to consider what happens when this second expression for concentration

$$C_H = \frac{\frac{q_{H \text{ in}} t}{V}}{1 + \frac{q_{H \text{ in}} t}{V}}$$

includes changes in the ambient pressure. Initially, an assumption was made concerning the pressure equilibrium across the exhaust vent, that is

$$Q_{\text{out}} = q_{H \text{ in}}$$

Now the reduction of ambient pressure with increasing altitude must be considered. The corresponding equation for pressure equilibrium becomes

$$Q_{\text{out}} = q_{H \text{ in}} + Q'_{\text{out}}(P_A)$$

Where $Q'_{\text{out}}(P_A)$ is the rate of flow which occurs due to the changing ambient pressure P_A .

The second assumption was that the H_2 concentration was homogeneous which allowed an expression to be written for the rate of flow of H_2 through the

exhaust vent. This same assumption could now be made and with a little effort an expression for $Q'_{out} (P_A)$ could be derived. Will this model be truly representative of the actual situation? The answer hinges upon the assumption that the H_2 concentration is homogeneous. In fact, all comments regarding the H_2 concentration made so far depend upon the homogeneity of the distribution. Most of the quantitative results in the reference discussed so far also depend upon this assumption. Are they valid? To answer this question it is necessary to examine the profile of the H_2 concentration for a leak.

If the leak is minute, the dispersion of hydrogen will occur primarily by diffusion. An experiment conducted by the Bureau of Mines⁽¹⁴⁾ gives an indication of the rate of diffusion of hydrogen into oxygen. (Similar results would be expected for the diffusion of hydrogen into nitrogen).

A cylinder 60 inches long and two inches in diameter was filled one-half with H_2 and the other half with O_2 . The gases were separated by a valve and the diffusion of the gases was calculated by the expression:

$$C(x,t) = \frac{C_o}{t} [1 - \text{erf} (\frac{x}{2\sqrt{Dt}})]$$

Where C_o = original concentration at the interface
 x = distance from the original interface
 t = elapsed time
 D = diffusion coefficient for the gases used
 and $\text{erf} (x / 2\sqrt{Dt})$ is the gaussian error function.

A plot of this equation is shown in Figure A8. From this figure it can be seen that the 4% level of H_2 was at about 25 cm after 120 sec. After 300 seconds the 4% level had traveled beyond 40 cm. The rate of travel was only slightly greater than

$$\frac{43 - 25}{300 - 120} = 0.1 \text{ cm/second.}$$

Calculated Concentration Distributions

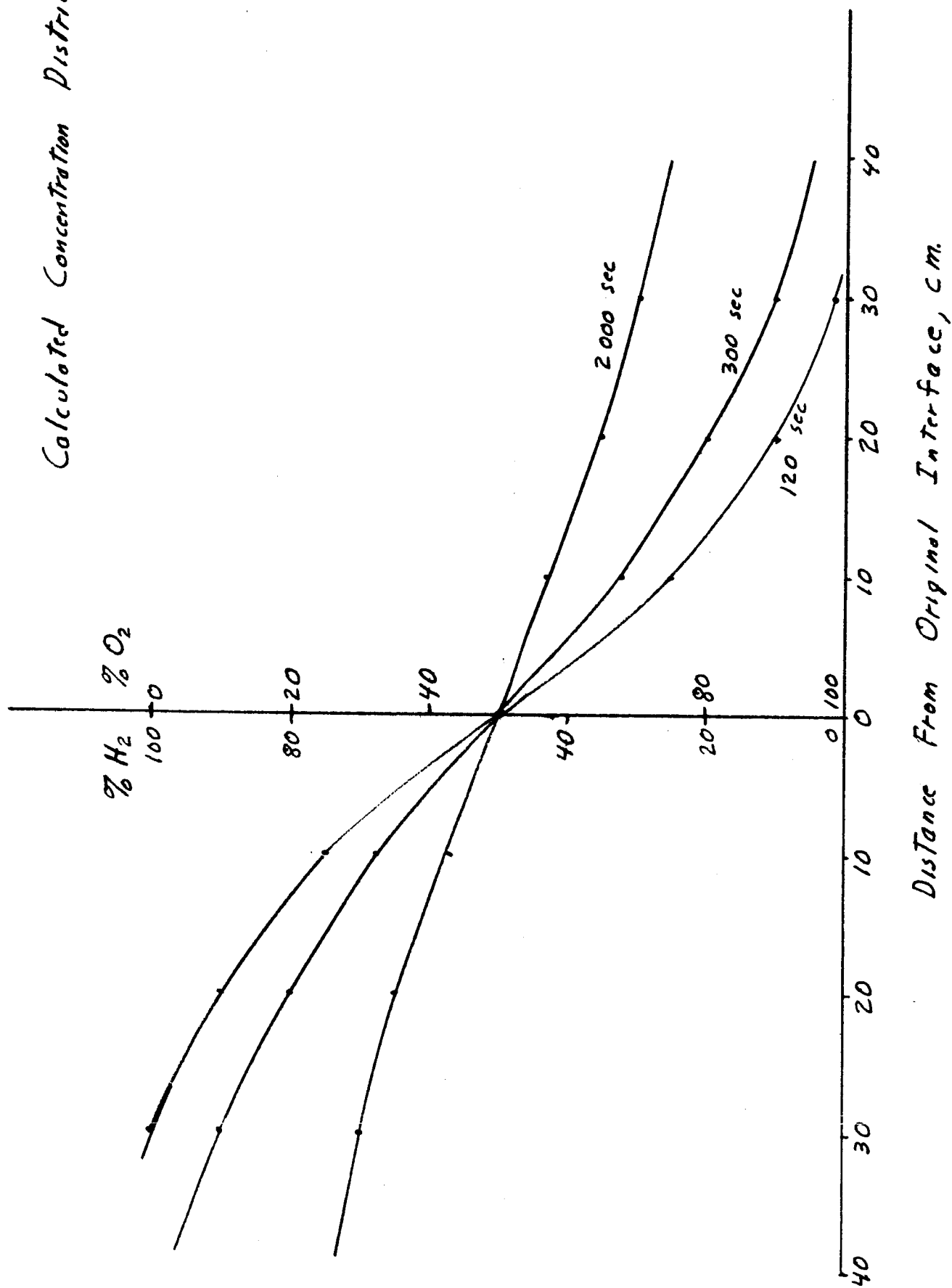


Figure A8

This example was purposely chosen to show a worst case rate of dispersion. In an interstage the rate of diffusion would be much higher because of geometry, convection effects, etc. Nevertheless the assumption that homogeneity is quickly established in all conditions is erroneous.

There are two references^(15,16) which give theoretical "plume" models that can be used as estimates of the concentration profiles of H_2 from a leak. Much work has been done with these profiles and an attempt has been made to verify the accuracy of the theoretical work by experiments with helium plumes.⁽¹⁷⁾ One objective of this work was to monitor the release of H_2 from spills of the cryogenic fluid of leaks. The quantity and location criteria for sensors as well as guidelines for optimum performance was desired for both outdoor and indoor leaks.

The plume models were developed for an open space, and constraints such as walls were not considered. The models do give an indication of what would happen during the initial phase of a leak in a large enclosure. Most of the data given in the references was in the form of the graphs shown in Figure A9; From this data, and empirical results using the measured values of buoyancy from a $10 \text{ ft}^3/\text{min}$ leak, the normalized scales in Figure A9 were evaluated for this special case. An approximate concentration profile is presented in Figure 10.

The leak rate of $10 \text{ ft}^3/\text{min}$ is slightly larger than the high nominal leak rate of the J2 engine. In fact, if the leak rate of the J2 engine was assumed to be $1500 \text{ in}^3/\text{min}$, and another leak such as that shown in Figure A10 were to occur, the combined rate would be $3000 \text{ in}^3/\text{min}$. This is the leak rate which would give an average concentration of 4% H_2 at .15 psi according to the sealed interstage approximation. Can such a leak be detected?

Two problems arise, location and time of travel; depending upon the location of the mass spectrometer in the plume an infinite number of build-up rates could be monitored. Also, assume the leak occurs on one side of the interstage and the mass spectrometer is on the opposite side, the rate of travel

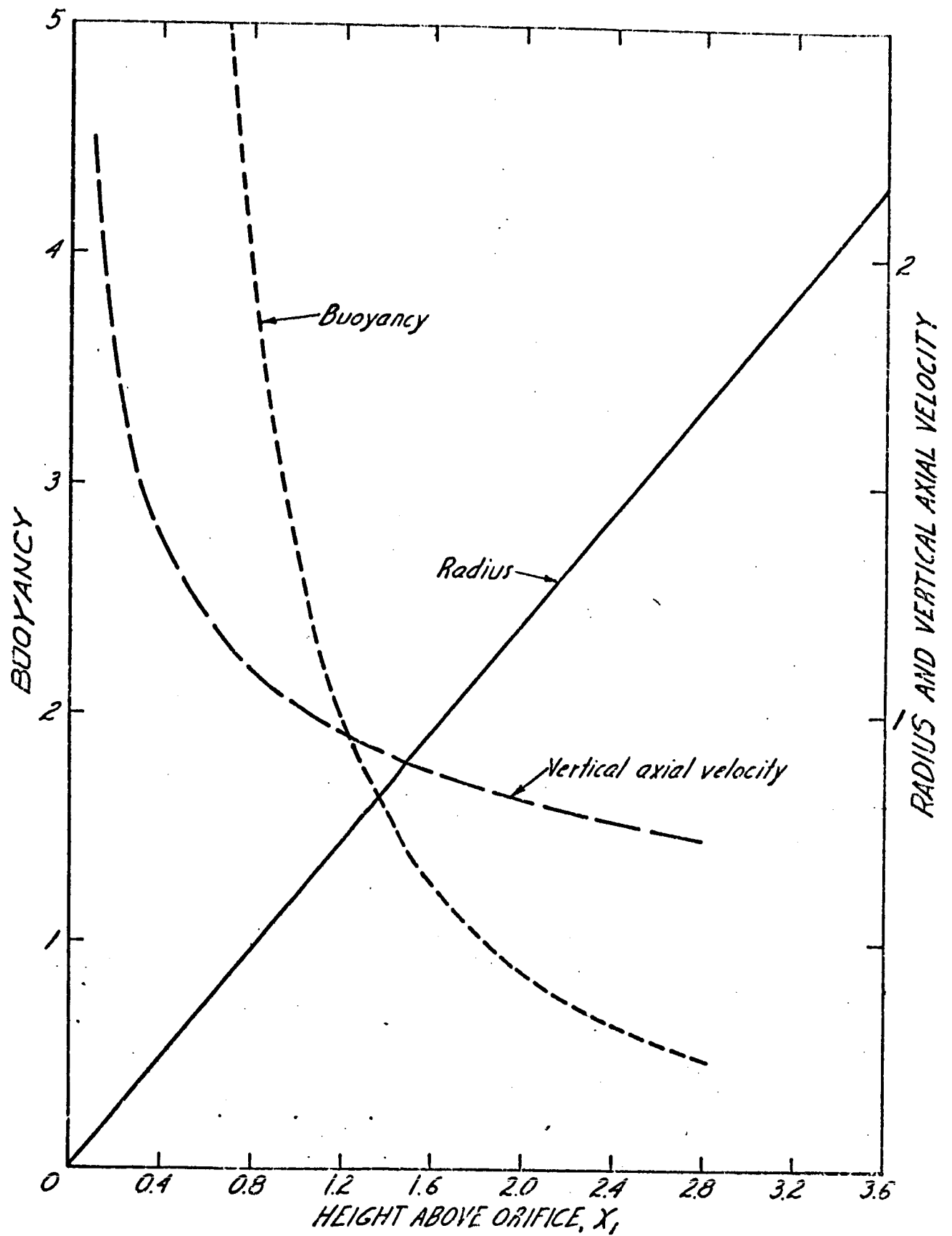
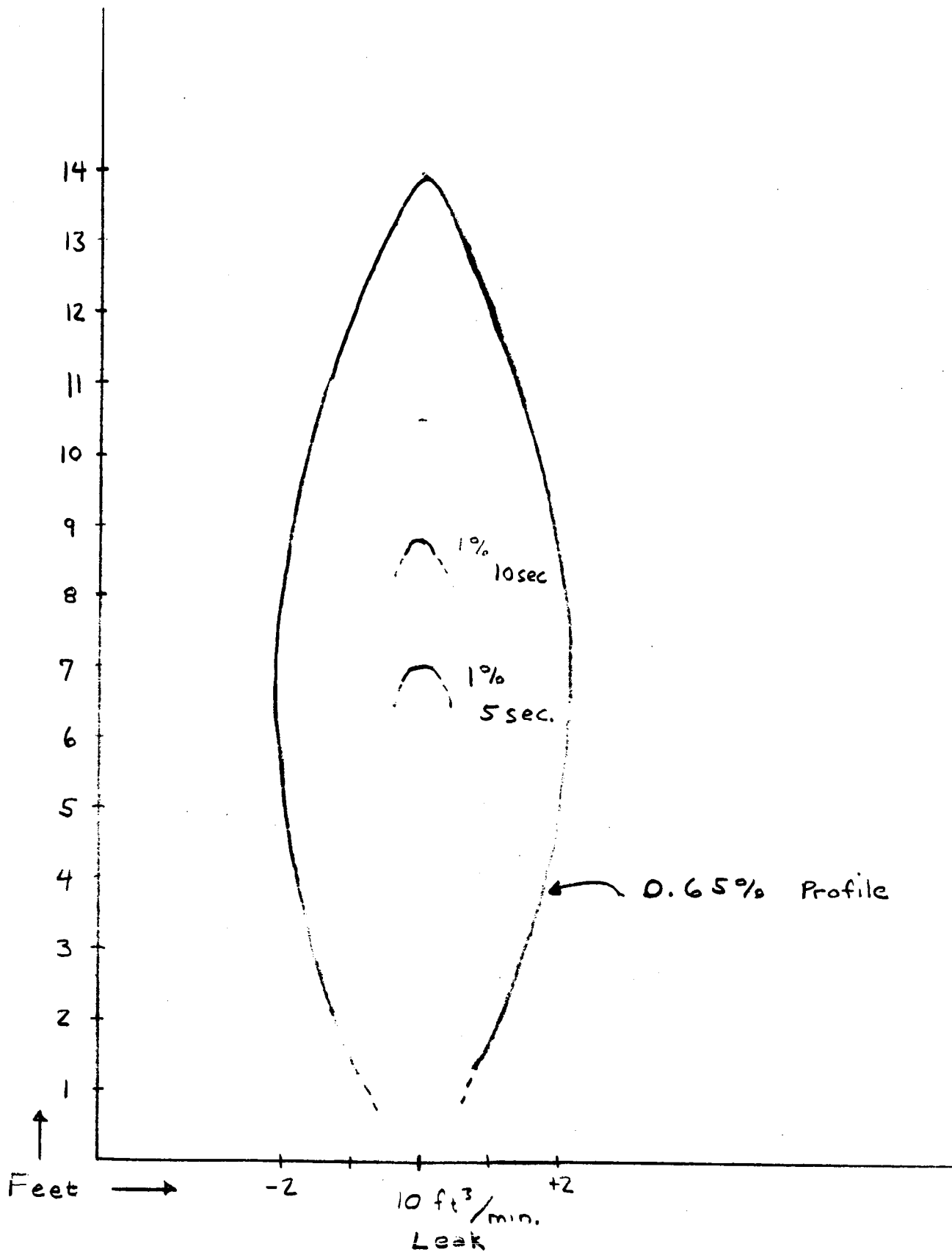


Figure A9 - Solution to the Non-Dimensional Equation
for a Plume in a Constant Density Environment.



H₂ Concentration Profile
After 10 seconds

FIGURE A10

for the one percent profile along the axis of the plume was calculated at approximately one-half foot per second after approximately 10 seconds. From Figure A10 it can be seen that this velocity decreases, increasing plume heights.

Approximating a linear rate of travel across a 30-foot interstage, however, the time for the one percent profile to reach the spectrometer would be

$$T = \frac{30 \text{ feet}}{.5 \frac{\text{feet}}{\text{sec}}} = 60 \text{ seconds} \\ = 1 \text{ minute.}$$

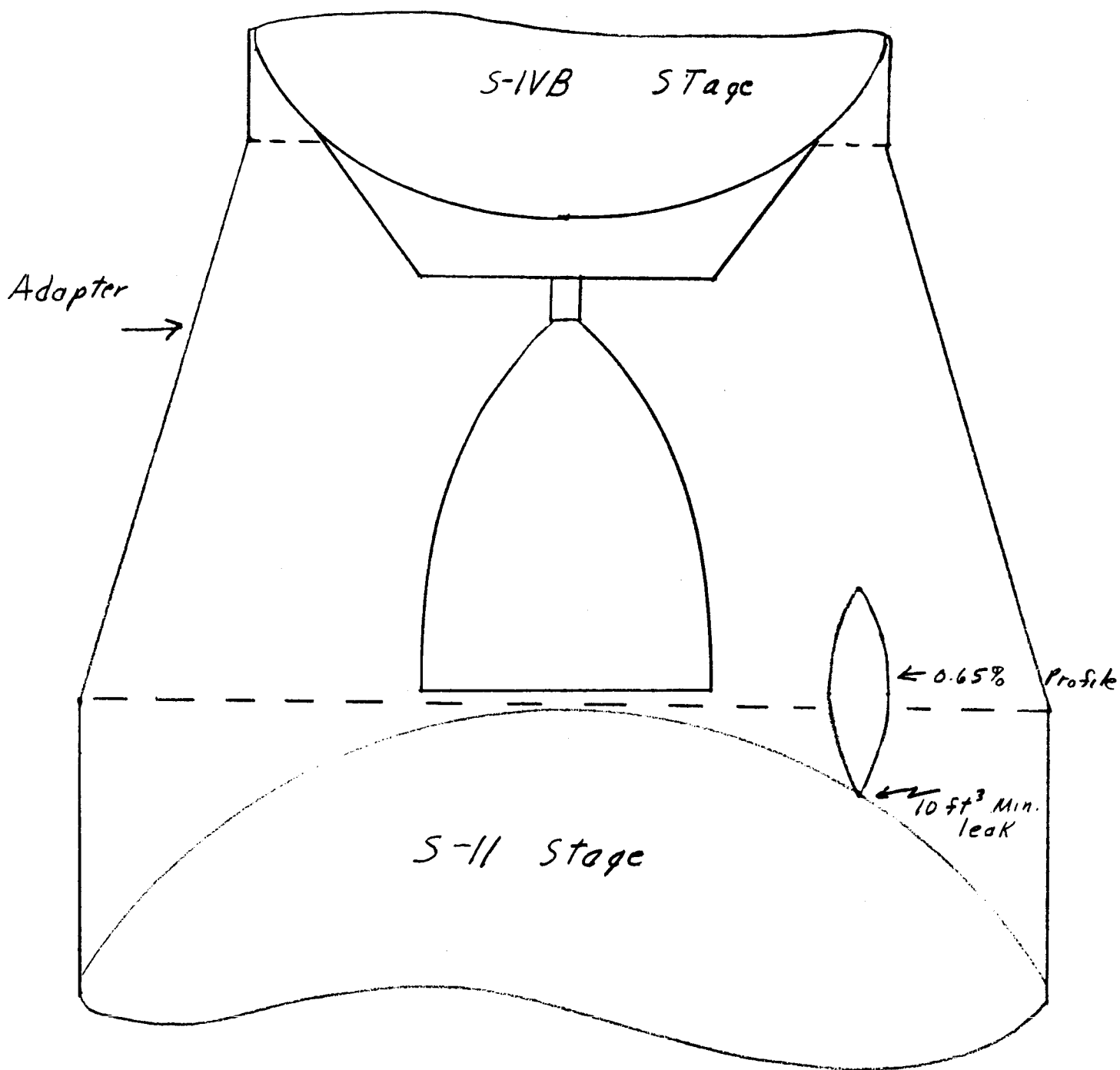
Clearly, by the time the one percent profile reached the detector, a large volume of the interstage might contain a concentration of hydrogen over the 4% range. In Figure 11, this profile has been plotted in the aft interstage of the S-IVB for purposes of demonstration.

Obviously, from this model, the assumption of a homogeneous concentration seems invalid. An expression for the flow rate of H_2 through the exhaust valve would be very difficult to derive if based on this model. Many variables would have to be considered.

The accuracy of this model is unsure at present. Experimental tests to verify the model using a H_2 plume have been difficult to implement⁽¹⁷⁾. In the experimental plume, convection from the surrounding atmosphere tends to disturb the profiles.

In this case, where the plume has been considered as occurring in the interstage, it is likely that the edges of the plume would have a higher concentration than the model. This would occur because the gas would be contained by the walls of the interstage. Also, convection from the inlet and outlet exhaust ports would disturb the profile. The actual plume would tend toward a homogeneous distribution.

As the missile altitude increased, the convection flow in the interstage



H₂ Concentration Profile
After 10 Seconds
Figure A11

would increase and the pressure would decrease due to the exhausting of the interstage gas. This would tend to cause the plume to grow faster and the profiles would be disturbed even more.

This is an area of effort which needs expanding. The plume model for a decreasing ambient pressure and convection flow should be derived. It would then be possible to determine the validity of a homogeneous model. At present, further effort on the derivation of a more accurate model of the average concentration of H_2 in an interstage during launch is not merited.

A few conclusions can be drawn from the plume model discussion. In the event of a leak from a pure H_2 source there will always be some volume having concentrations ranging from 95% H_2 to 4% H_2 . If there is a simultaneous 4% O_2 concentration, an ignition source and an ambient pressure greater than 0.15 psi, a reaction will take place.

The locations and the number of mass spectrometers can be determined accurately only if further development of a plume model in an interstage is undertaken. Qualitatively it can be stated that the probability of determining the extent and location of a leak is proportional to the number of sensors or concentration monitoring locations. In addition, it is probable that one or two sampling locations per interstage would not be sufficient.

The placement of the spectrometers would be constrained by the practical structure and space limitations as shown by the black boxes shown in Figures 2 and 3. The sampling locations should be near the propellant feed lines, connectors, valves, tank seams and ignition sources.

The exact locations should be dependent on a more exact plume model and on a failure effects and reliability analysis. Some of the failure effects information may be available but the time allotted for the study is not sufficient to achieve a greater level of detail or a more extensive plume model.

3.3 HYPERGOLIC LEAKAGE

The consideration of hypgolic leaking is analogous in many respects to H_2 or O_2 leakage. Due to the toxic effects of hypergolics, however, it is necessary to rate sensitivity in the monitoring instrument. Toxic effects are of particular concern in spacecraft and orbiting workshops so this discussion will be delayed to section 4.0 S-IVB workshop.

3.4 PASSIVE SENSING

One possible application of a mass spectrometer in addition to hazards monitoring in the interstage areas is passive sensing. Passive sensing determines if systems are operating correctly by monitoring secondary effects. Seeded chemicals placed on components are released by temperature, vibration, or mechanical abrasion of the components. These chemicals could be sensed by a mass spectrometer and the information could be used as checkout data.

This method of checkout is at the laboratory experimental level and current development activity is low. Much work would be needed to qualify a chemical sensor system as a candidate for any but very specialized spacecraft or launch vehicle tests. Finally, chemical sensors are not favored for spacecraft checkout because of the relative non-specificity of the information and the possible undesirable side effects of toxicity.

4.0 GAS MONITORING IN THE S-IVB WORKSHOP

The initial purpose of this part of the study was to examine the problem of monitoring residual hydrogen during the process of S-IVB tank passivation. The mass spectrometer system for accomplishing this job was then to be defined and evaluated.

Recently the application of the mass spectrometer as a caution and warning monitor in the orbital workshop cluster has become of interest. To the extent time has allowed, both of these functions were considered.

4.1 S-IVB WORKSHOP DESCRIPTION^{18, 19}

An outline drawing of the S-IVB workshop is shown in Figure A12. A full scale mockup of this workshop is on display at MSFC. This mockup includes most design concepts. Two off-the-shelf Saturn S-IVB stages will be modified for the orbital workshop missions.

Major modifications include a triangular aluminum grid construction of the floor and compartment walls. Special push-in fasteners will be used to attach equipment to these walls. A double floor is located near the middle of the stage and it consists of the same type grid work. Walls of the food and waste management compartments are covered with thin aluminum sheeting. The living area has a fabric lining for thermal control and ventilation. The fabric will be strong and porous with perforations to aid ventilation.

The interior of both compartments is equipped with a thermal curtain which allows 1.5 inches of annular space between the curtain and the tank wall. This space is used for ducting the atmosphere by fans allowing better temperature control and circulation.

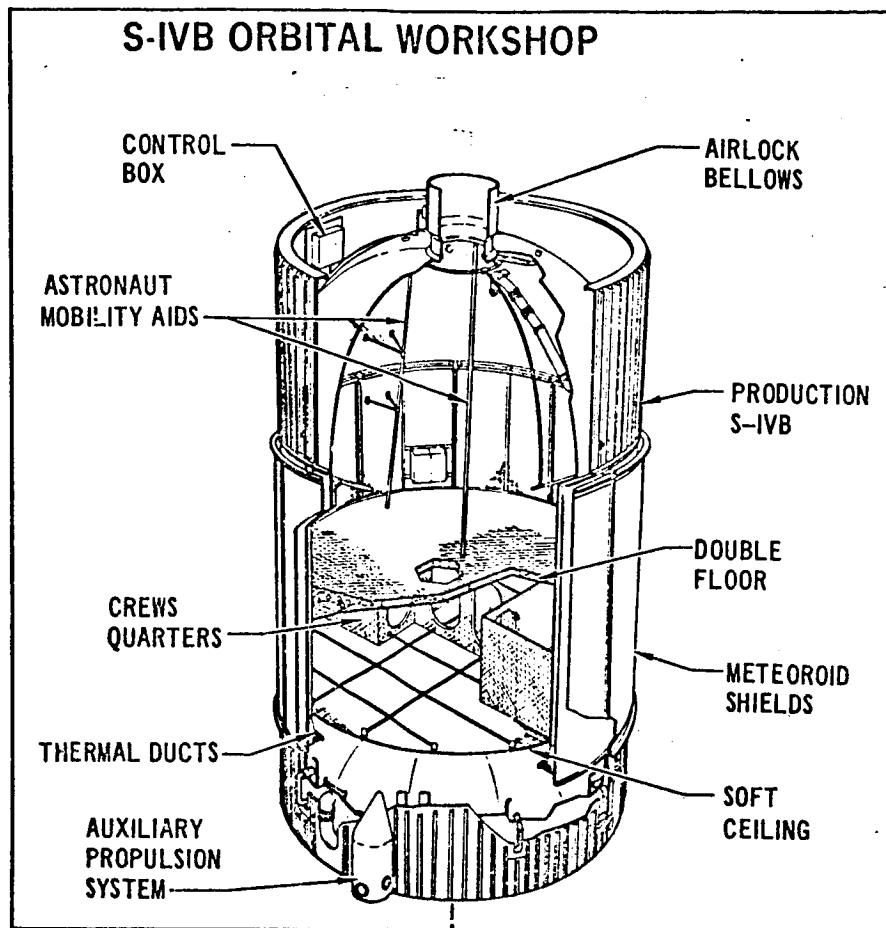


Figure A12

Much equipment, including the ventilation fans, will be stored in the air lock and brought aboard for installation by the astronauts. Most electrical wiring will be installed in advance.

Eight 2.7 amp nickel cadmium batteries will be available in the air lock. Solar arrays, which will provide six kilowatts, will be extended in orbit.

All sealing devices for the LH_2 vents must have maximum ease of installation and zero leakage. The tank will be pressurized to 5 psi from a supply carried in the air lock. The mixture will probably be 3.5 parts oxygen to 1.5 parts nitrogen.

4.2 MISSION DESCRIPTION

The workshop will have an orbital life of one year. It will be inhabited two times during this period, once for four weeks and once for 56 days.

After attaining orbit the tank or workshop will be passivated. This procedure is defined by three phases. After burnout all remaining H_2 and O_2 are vented through the engine. Since the ambient pressure at orbital altitudes is 10^{-7} torr or lower, see Figure 7, most gases should be vented overboard.

All pressure vessels containing nitrogen and helium are thus vented. Five hundred sensors are used to monitor the results of this phase.

After telemetry check all valves are closed and the sealing devices are installed permanently into the six apertures in the tank by the astronauts. The tank is then filled with the N_2 - O_2 atmosphere and equipment installation begins.

During the time the astronauts inhabit the workshop various experiments will be conducted. Maneuverability and work efforts will be monitored. Various experiments to attain biomedical data will be performed.

4.3 PASSIVATION HAZARDS

One major concern in passivation is the residual H_2 which may be left after the exhausting phase has taken place. Clearly the low pressure of space should provide a good pumping action for the residual hydrogen. If the conductance is high enough and the exhaust time is long enough the gaseous pressure of H_2 in the workshop area should approach a very low pressure.

Two phenomena may occur which are potential hazards. There may be residual hydrogen gas trapped in the pre-installed equipment which cannot be exhausted in the length of time allowed. Or, there may be a collection of H_2 which remains in a liquid state in some isolated area of the workshop after the allowed time for exhausting.

4.3.1 Trapped H_2 Gas

One piece of equipment which might be anticipated to trap residual H_2 gas is the thermal curtain, which will be pre-installed. After the LH_2 is loaded, the liquid will permeate this curtain. After the tank is evacuated the gaseous H_2 within the curtain will diffuse out. This

diffusion will depend upon the pressure differential, the diffusion constant of H_2 in the material, and the temperature profile in the region of the thermal curtain.

To describe this phenomenon analytically would be involved. In fact, the characteristics of H_2 diffusion in the type of material to be used for the thermal curtain may have to be measured to determine the diffusion coefficient. Some calculations can be made, however, to determine how much residual H_2 gas would be a problem. From Figures A5 and A6 it can be seen that for the pressure and mixture in the workshop a H_2 concentration of 4% would be hazardous. The partial pressure of 4% H_2 would be 0.2 psi. Now assume that H_2 is trapped at 1 atmosphere of pressure and at a temperature of 23°K. If no hydrogen escapes until after passivation, the equivalent volume of H_2 would be

$$V_{\text{Final}} = \frac{15 \text{ psi}}{5 \text{ psi}} \frac{300^\circ\text{K}}{23^\circ\text{K}} V_{\text{Initial}}$$

$$= 40 V_{\text{initial}}$$

Some assumption must be made concerning the homogeneity of H_2 and a similar problem occurs here, as mentioned in Section 3.2.5. For this initial estimate, however, a homogenous distribution of H_2 after passivation will be assumed.

The volume of the H_2 tank is approximately 8,000 cubic feet.²⁰ A 4% volume of H_2 would be about 300 cubic feet. At the initial conditions previously assumed the amount of H_2 could be trapped in a volume of 7.5 cubic feet. The thermal curtain will have an area of about 1,500 square feet and a depth of a few inches.¹⁸ If the depth is 6 inches, the volume will be 750 cubic feet.

From the previous calculations and assumptions it can be anticipated that a decrease of the gaseous H_2 trapped in the thermal curtain, of two orders of magnitude during exhausting, would bring the homogenous concentration to safe limits. Considering the pressure differential produced by exhausting and a long period of time for exhausting this decrease of H_2 in the thermal curtain should be achievable.

There are two sources which tend to confirm this conclusion. One source indicated that some testing of H_2 diffusion through typical insulation has been undertaken, and there seems to be no problem.² The other source is substantiated from data taken from the January 22, 1968 Saturn flight. The first phase of tank passivation was tested. The original estimates were validated, that is, "All propellant and high pressure gases were vented overboard...passivation can be accomplished in a reasonable time period." 18

4.3.2 Trapped Liquid H_2 or Solid H_2

The second phenomenon which was mentioned in section 4.3 as a potential hazard is the trapping of residual H_2 in the liquid state. After the S-IVB stage reaches orbit there will be some LH_2 remaining to be vented overboard. At first thought it seems unlikely that any hydrogen could remain in a liquid state when subjected to the low pressures encountered in the exhausting phase. A more detailed look at evaporation, however, shows the possibility.

As molecules escape from the surface of a liquid the temperature of the liquid decreases. The reason for this is that the temperature of a liquid is a measure of the average kinetic energy of the molecules. The molecules that escape have a higher kinetic energy and therefore the average

kinetic energy of the remaining molecules is lower. The liquid is continually cooled and it is possible for a low temperature liquid to be maintained. The boiling point of H_2 is 23°K.

If no heating is experienced it should be possible for solid hydrogen formation to take place. The evaporation can cause cooling to the melting point, 14°K, of H_2 . Some subliming would take place but the vapor pressure decreases rapidly in this temperature region. For example at 20°K the vapor pressure is 1 atmosphere but at 15°K the vapor pressure decreases to 0.13 atmospheres. In a solid state hydrogen could therefore be expected to be exhausted to space at a much slower rate than vapor from the liquid state.

From a qualitative theoretical point of view it could be suspected that solid hydrogen might form and that the pumping rate of this solid hydrogen during passivation would be low.

There is at least one source of information that predicts on a quantitative basis that solid hydrogen could form by this process on the concave metal surface of space vehicles. This formation could take place if sufficient cooling of that surface by liquid H_2 had taken place previously.

One area in which solid hydrogen might form inside the S-IVB stage is the thermal curtain. Since the rate of heat transfer in the thermal curtain would be low, liquid hydrogen might evaporate rapidly enough to cool some of the H_2 to the solid state. The heat transfer into the thermal curtain in a low pressure environment would be dependent

mainly on thermal radiation from the tank walls. The walls would be heated primarily by solar radiation. It is possible for the exterior skin to reach high temperatures on some sectors so this heat transfer should be high.

After passivation and pressurization, the heat transfer would be controlled primarily by convection, and any solid hydrogen remaining would be quickly heated to the gaseous state. To determine what amount of H_2 would constitute a hazardous situation a homogeneous distribution will again be assumed.

The amount of gaseous hydrogen at 23°K which would give a 4% concentration after pressurization in orbit was calculated to be 7.5 cubic feet. The density of the liquid is higher than the density of the gas by a factor of 53 at the boiling point of H_2 . The same amount of hydrogen gas could be trapped in liquid form in a volume of .14 cubic feet and would weigh 0.6 pounds.

Since 0.6 pounds of H_2 would be hazardous the question is: Can 0.6 pounds of liquid or solid hydrogen be sustained through launch and passivation? The answer to this question can be determined analytically only by a rigorous heat transfer analysis. Some work in this area has been done. For example, the amount of LH_2 in the S-IVB stage which is lost by solar heating in an earth to moon transfer orbit has been determined. Also, the amount and periods of solar exposure on various sectors of the S-IVB stage has been determined for various orientations. These results can be used to calculate the radiation transfer to the thermal curtain. By measuring the thermal conductivity of the thermal curtain and calculating the evaporation and cooling rate of LH_2 in the curtain and other collection

locations in the S-IVB, final estimates on the residual LH₂ can be determined.

Due to the complexity of the problem and the lack of sufficient data on the thermal curtain and LH₂ interaction with the curtain, it is not possible to obtain any quantitative data during the short time of this study. Since the possibility of a potential hazard has been proposed, it may be worthwhile to examine the problem further either empirically or analytically. Although the comment was made that the June 22, 1968 Saturn passivation test was successful, it may be well to examine the data more carefully. Surely the sensors showed the level of gaseous H₂ during passivation, but the job of monitoring residual LH₂ or solid H₂ would be much more demanding, especially since 0.6 lbs. is a small quantity and the vapor pressure would be very low for solid H₂. Nevertheless, the survival of 0.6 lbs. of LH₂ in the presence of high radiation transfer from the walls is unlikely.

4.3.3 Mass Spectrometer Sensor

Mass spectrometer instrumentation inside the S-IVB workshop could be used to detect gaseous, liquid or solid hydrogen. The mass spectrometer analyzer operates at a pressure of 10^{-6} torr and therefore has the required sensitivity to detect and locate trapped H₂ gas, liquid, or solid. Most hydrogen sensors which are used for hydrogen detection operate at a much higher pressure level. Since the pressure inside the S-IVB would be greater than 10^{-6} torr, a sampling orifice and a vacuum must be used.

It would be very difficult to design a mass spectrometer system which could be stored in the cryogenic atmosphere. The system must therefore

be portable for storage in the air lock module and later transfer to the workshop. Due to the requirements for non-cryogenic storage and use before oxygen pressurization the system must be carried into the inert workshop atmosphere by an astronaut wearing a pressurized pressure suit.

The best time to search for residual gaseous, liquid or solid H_2 , if this is indeed a problem, is at the time of vent sealing. Possibly the best system would be one with self contained battery power, so that the astronaut could drift in a predetermined manner along the walls of workshop and measure H_2 concentration profiles. A thorough search of the interior could be made during or prior to the time that another astronaut was sealing the vent ports.

After the search was completed the unit could be plugged into the socket of the triangular grid work. A high pressure sampling inlet could be activated and the unit could operate after pressurization as a caution monitor for H_2 or as a caution monitor for a variety of gases depending on the designed mass range.

The implementation and many design characteristics of a mass spectrometer system used on board the orbital workshop are similar for a variety of applications of the instrument. For this reason another application will be considered before discussing system details.

4.4 CAUTION AND WARNING MONITOR

A sensor to identify and monitor the partial pressure of various gases is needed in the orbital workshop after pressurization. The instrument would be a part of the caution and warning system which alerts the crew to hazardous conditions or an impending dangerous condition within the OWS cluster. Caution is defined as an impending dangerous condition requiring attention but not necessarily immediate action. Warning is defined as a hazardous condition requiring immediate corrective action or evacuation.

The caution system consists of sensors, and an indicator/controller panel. The sensors detect an impending dangerous condition and provide a signal to the indicator/controller panel. The crew-installed indicator/controller panel is located in the crew quarters area and contains an amber indicator light for each sensor. The panel also contains an indicator light/controller logic test switch and a master caution light reset switch.

The caution system is designed so that caution sensors will illuminate the master-caution amber indicator light on the panel. It also provides a discrete 28 vdc caution signal to the AM to initiate an alarm tone and light a caution light on the intercommunication panels in the AM, CSM, and ATM. The master caution reset switch is capable of deactivating the signal to the AM, CSM, and ATM, and turning off the master-caution light in the OWS, but it does not inhibit operation of the remaining caution system parameters.

The warning system consists of sensors, an indicator/controller panel, and an intercommunication alarm. The sensors detect a hazardous condition and provide a signal to the indicator/controller panel. The crew installed indicator/controller panel is located in the crew quarters area and contains a red-indicator light for each sensor. The system also contains an indicator light/controller logic test switch, a warning alarm tone reset switch, and sleep switches.

The alarm system is designed so that sensors will illuminate the master-warning red-indicator light on the panel and provide a discrete 28 vdc warning signal to the AM. The signal turns on the alarm tone and lights a red-warning light on the intercommunication record in the AM, ATM, and CSM. An AM generated warning tone is transmitted through the intercommunications system to the OWS communications disconnect receptacle. The alarm tone reset switch is capable of deactivating the AM-generated alarm tone in the OWS. The indicator light remains illuminated until the malfunction is corrected. The reset switch does not inhibit operation of the remaining warning system parameters. The sleep switches inhibit all communications and alarm tone in the OWS sleep areas, but the controller logic includes a sleep switch override for the warning alarm tone. The system operates from one AM bus, either "A" or "B", and has the capability to automatically switch to the second bus in the event of a bus failure. It is designed so that single point failure will not prevent the alarm signal from reaching the AM circuit.

4.4.1 Mass Spectrometer As A Caution Sensor

The function of one sensor in the caution and warning system is to monitor the major atmosphere constituents, i.e., oxygen, nitrogen, helium, water vapor, and carbon dioxide partial pressures. Another function of this sensor may be to monitor trace contaminant concentrations. Automatic and manual modes of operation could be provided with both analog display and alarm signals. Complete contamination data could be telemetered to ground sites for periodic detailed analysis. The ideal sensor to perform these functions is a mass spectrometer capable of a varying scan modes.

The sampling inlet must provide a means of supplying a representative sample of cabin atmosphere to the spectrometer. Since the small orifice can be clogged by dust particles, the orifice must be protected by a filter. A filter must be chosen which will not limit the instrument response.

Due to the redundancy of peaks for some elements, a determination of which peak to use for the partial pressure measurement should be made.

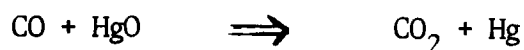
Under electron bombardment in the ion source, some of the gas molecules are disassociated into molecular fragments of their constituent atoms. This gives rise in the mass spectra to a mass peak for each fragment of the parent molecule. These peaks along with the peak resulting from the parent molecule are known as the "cracking pattern" for that species. This cracking pattern is unique for each gas and is, in effect, a "fingerprint" which can be used to identify it. In analysis of large organic molecules, the disassociation of the parent molecules leads to a myriad of peaks in the mass spectrum which often obscures the presence of trace quantities of some species. On the other hand, the cracking pattern can be used to determine the relative amounts of two species, both of which make a major contribution to the spectrum at identical masses.

As an example, consider the gas, carbon monoxide (CO). Carbon monoxide has a mass of 28 AMU. Under electron bombardment, the following species are produced: CO^+ , CO^{++} , C^+ , and O^+ in addition to the species $\text{C}^{12}\text{O}^{16}$, $\text{C}^{12}\text{O}^{17}$, $\text{C}^{13}\text{O}^{17}$, and $\text{C}^{12}\text{O}^{18}$ which are due to the isotopes of carbon and oxygen. The mass spectrum of carbon monoxide, therefore, will yield peaks at masses 12, 14, 16, 28, 29, and 30. (Peaks at 13, 17, 18 and 31 are also possible; however, they are small compared to the 28 peak and rarely are detected in a CO spectrum). If the peak height of each peak is recorded and normalized to mass 28 (parent peak = 100), this is known as the cracking pattern for carbon monoxide.

If an analysis is made of a gas consisting of carbon monoxide and nitrogen, both of which have their parent and major peaks at mass 28, the respective cracking patterns are used to determine the contribution of the total peak height of each of the two gases. Nitrogen, being a diatomic gas consisting of two similar atoms, yields a spectrum having only a peak at mass 14 (due to both N_2 and N) in addition to the parent peak at mass 28 and isotopic peak at mass 29. Thus, by using the heights of the peaks at 12 and 16 and the

known cracking pattern of carbon monoxide, the peak height of mass 28 due to CO can be calculated and subtracted from the remainder and is obviously due to nitrogen.

Another method for determining CO is to measure it indirectly. A mercuric oxide reaction chamber would provide an indirect method of determining carbon monoxide. Carbon monoxide reacts quantitatively with mercuric oxide at 200°C according to the reaction.



This is the adaption of part of the method described by V. Tomberg, (Experientia 10, 388-9, 1954) by which he reported measurement of 1 part of CO in 100 million parts of air. The method consisted of reacting the CO in an air sample with mercuric oxide in a heated tube, and determining the mercury vapor released by means of atomic absorption spectroscopy. Mass spectrometry would not be quite as sensitive, but there is good reason to believe that the full dynamic range of the monopole mass spectrometer would measure values as low as a few parts per million of carbon monoxide using this method. To achieve such a measurement, it might be necessary to use isotopically pure mercury, as natural mercury atoms are distributed between five isotopes and would distribute the signal correspondingly. As to the hazard presented by bringing mercuric oxide aboard a spacecraft, the amount needed would be so small that it could all be ingested by a crew member with no ill effects. Six micrograms of mercuric oxide would be

sufficient to react with all of the carbon monoxide in a 6 cc sample containing 100 ppm of CO. In practice several milligrams of mercuric oxide would probably be used to insure that every CO molecule in the atmospheric sample contacted the mercuric oxide. Even this amount is insufficient to cause mercury poisoning. The mercuric oxide reaction chamber and the spectrometer tube should be insulated together. By careful design of the insulating jacket, the average power input to the tube will be sufficient to maintain both the tube and reaction chamber at 100°C. The advantage of operating the tube at this temperature is that it will prevent water vapor from being absorbed by the interior surfaces of the tube, and thereby permit measurement of water vapor along with the other atmospheric constituents.

4.4.2 Scan Modes And Readout

In the automatic mode of operation, the control circuitry would permit the monitoring of the four major atmosphere components, compare the resulting output with predetermined limits, and initiate an alarm if any of these four components exceed the limits in either direction. Also, periodically, a complete search of the mass spectrum would be made automatically for trace gases. If predetermined concentration limits are exceeded, an alarm could be actuated. If the alarm is actuated, the astronaut can switch to the manual mode of operation to determine the specific out of limits mass source causing the alarm signal. He may also arrange for telemetry to a ground station of the complete spectrum for analysis by mission scientists.

4.4.3 Calibration Circuitry

It has been observed in testing the mass spectrometer that the sensitivity varies due to a changing gain in the electron multiplier. This gain should stabilize after an initial rapid aging. Any change in gain after this time would be very slow, unless the chemical nature of the sampled gases could deteriorate or reactivate the dynode surfaces. In the presence of an atmosphere which is subject to only small changes in constituents, such as the S-IVB workshop, the gain change of the electron multiplier may be maintained at a minimum. Further testing will be necessary to verify this.

If the sensitivity change is found to be above tolerable limits, gain correction circuitry must be provided to compensate for the sensitivity. A method for accomplishing this as well as correction for the ionization efficiencies of the major constituents is to use two amplifiers at the spectrometer output.

The output of the spectrometer tube is connected to two gain-controlled amplifiers A1 and A2. The first of these, amplifier A1, is used to calibrate the total spectrometer tube gain. This is accomplished by removing the RF and DC voltages from the spectrometer tube for a short period during which a known output signal will be present due to the ionization and collection of the complete gas sample. The gain-controlled amplifier A1 serves to set the voltage at a constant value during this period, independent of the electron multiplier gain and any change in sensitivity of the spectrometer tube. Basically, this accomplishes a gain calibration at the beginning of each major component sweep.

The second gain controlled amplifier A2 converts the relative gas percentages to gas partial pressures by multiplying the percentages by a magnitude that depends on the cabin atmosphere total pressure and the gas ionization efficiency. Thus, for example, should the cabin pressure fall by 20% for any reason, this amplifier gain would be reduced accordingly so that the partial pressures for each mass peak would be similarly decreased. The input for the gain control would have to be supplied from a separate total pressure gage. The inclusion of this second gain-controlled amplifier is necessary in the manual mode to adjust the total spectrometer tube gain to compensate for differences in the ionization efficiencies of the four major gases.

4.4.4 Vacuum Pumping

The most critical problem in this application is to determine the type of pumping which is most critical. Although the space vacuum of 3×10^{-8} torr might be acceptable, it is impossible to vent to this pressure directly. Since the workshop will be surrounded by a meteoroid shield, the pumping port would probably have to vent to the annular space between the tank and shield. First order calculations have shown that a typical pressure here would be 2×10^{-7} torr. The background is too high for accurate spectrometer operation. For this reason an ion pump will be required

No non-magnetic vacuum pump has been found which is suitable. All other pumps require too much power. The General Electric Company has recently an ingenious concept for a light weight, low power, low fringing flux ion pump, which should be suitable for the S-IVB workshop application. The fringing field can be reduced to a region such that a magnetometer in operation on the S-IVB workshop would not be disturbed.

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APPENDIX B

PRINCIPLES OF OPERATION OF MONOPOLE MASS SPECTROMETER

The principle of operation of monopole and quadrupole mass spectrometers is identical; the former being a special case of the latter. In a quadrupole, an electric field is produced by four hyperbolic or cylindrical rods positioned as shown in Figure B.1, which is an end view. The field, produced by applying a voltage $\phi_0 = U + V \cos \omega t$ to the opposite pairs of electrodes, increases linearly in strength with distance from the field axis. If one draws equipotential lines in the cross section of the assembly, there is a region defined by a cross rotated 45° to the coordinate axis which is always at zero potential. In the monopole a V shaped electrode, held at ground potential, is inserted at the cross position relative to one rod and the other rods are eliminated. The field between the rod and V block is described by the same equations as the generalized quadrupole field.

The equations of motion for ions under the influence of the quadrupole field are known as Mathieu functions. Two classes of solutions exist; those in which x (or y) remains limited as t approaches infinity (stable solutions), and those in which x (or y) increases without limit as t approaches infinity (unstable solutions). These equations are usually solved in terms of dummy variables

$$E = \frac{\omega t}{2} \quad a = \frac{8eU}{mr_0^2} \quad q = \frac{4eV}{mr_0^2 \omega^2}$$

to determine the range of (a, q) over which stable solutions exist. This process yields a "stability diagram" which defines the conditions of stability under which a monopole can be operated. This diagram is shown in Figure B.2. In addition to having a stable trajectory, ions must have a maximum x (and y) amplitude less than the field radius or they will strike the pole pieces before reaching the end of the analyzer.

The monopole imposes one additional constraint if ions are to reach the detector. The y stable solutions represent a beat of finite amplitude in the y direction about the z axis of the tube. Because of a monopole's construction, even though an ion has a stable trajectory it will not reach the detector if its half-beat length is shorter than the field region. Thus ions which would be detected in a quadrupole will not be detected by a monopole if their beat length is too short.

Quadrupole Field Configuration

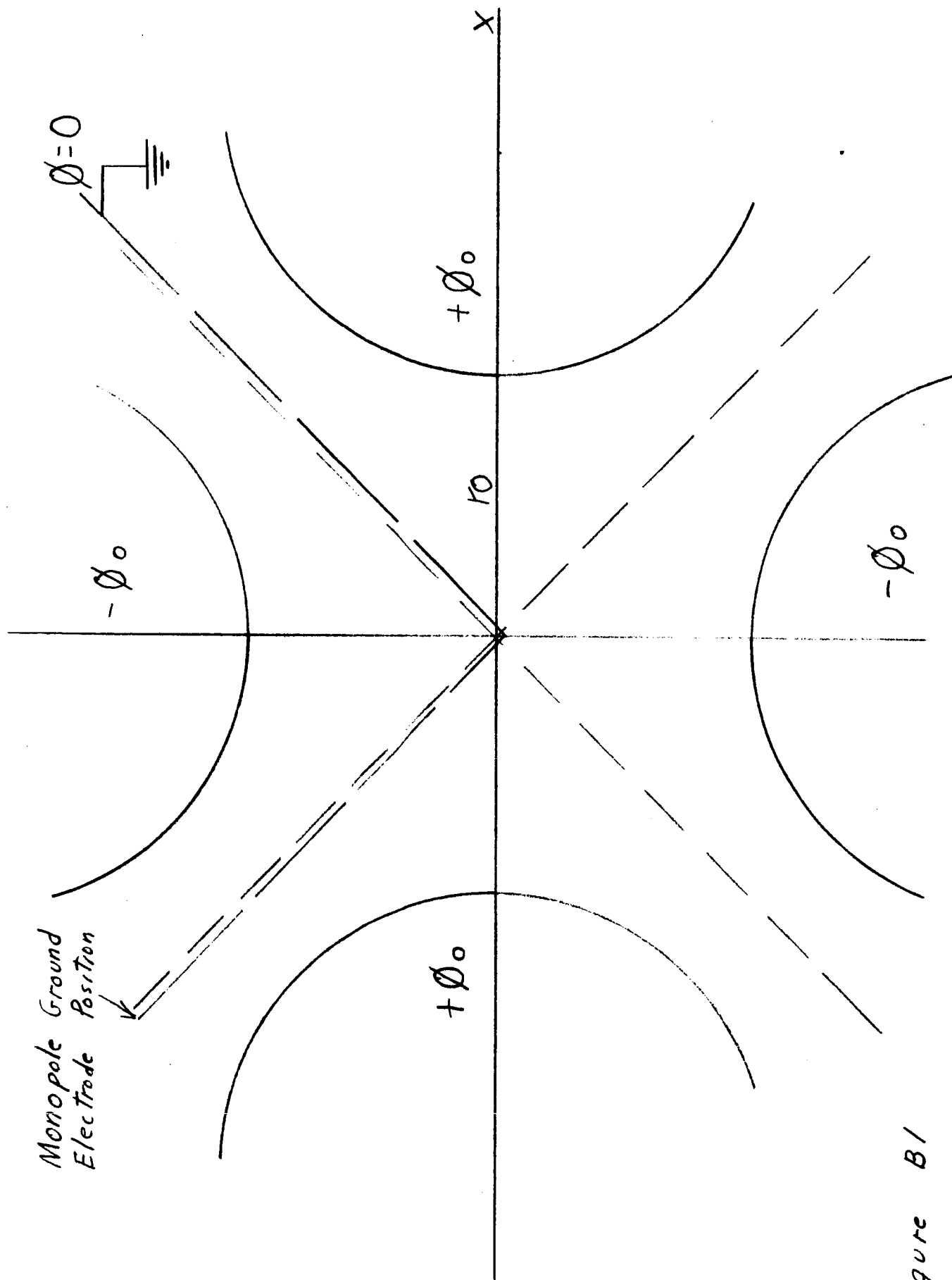


Figure B1

Quadrupole Monopole Stability Diagram

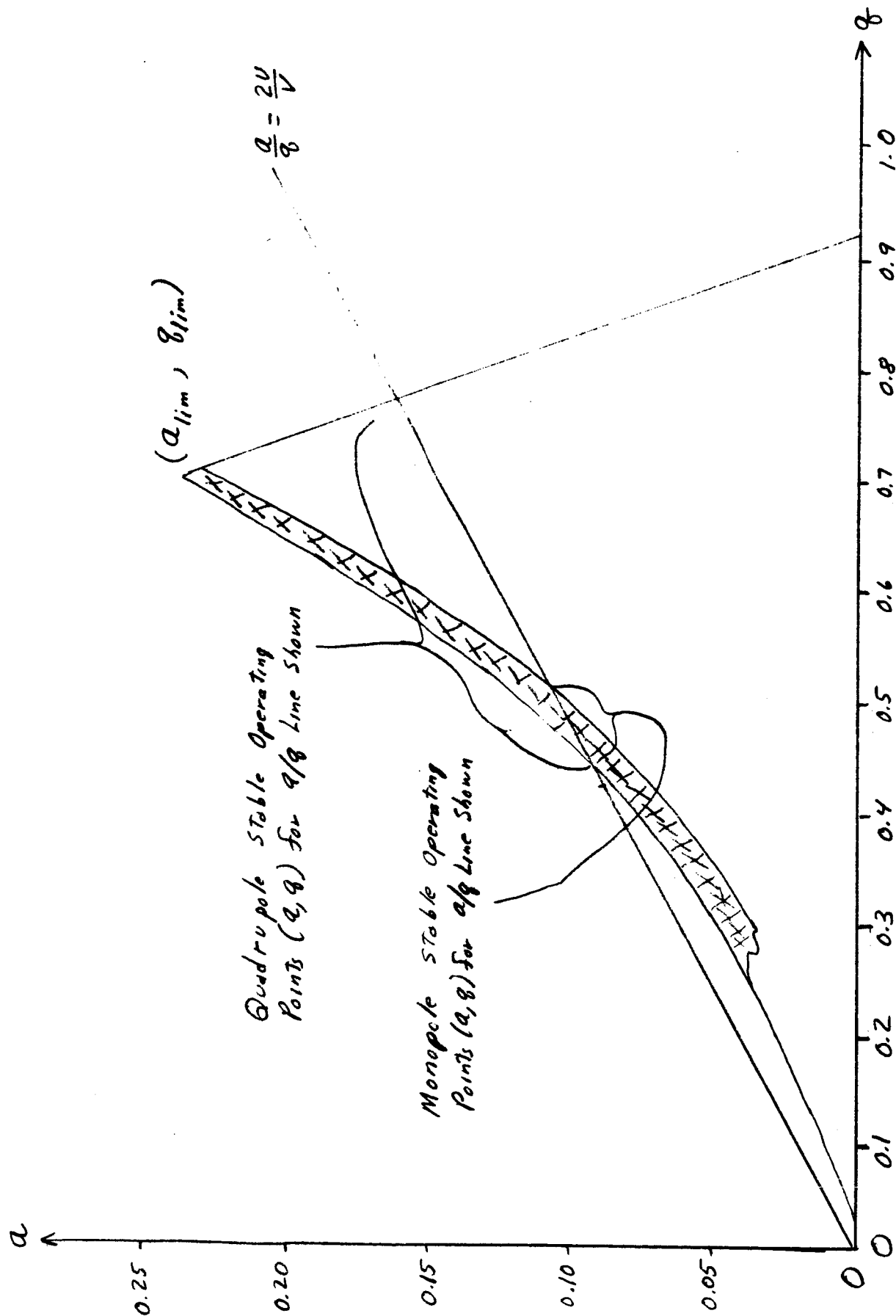
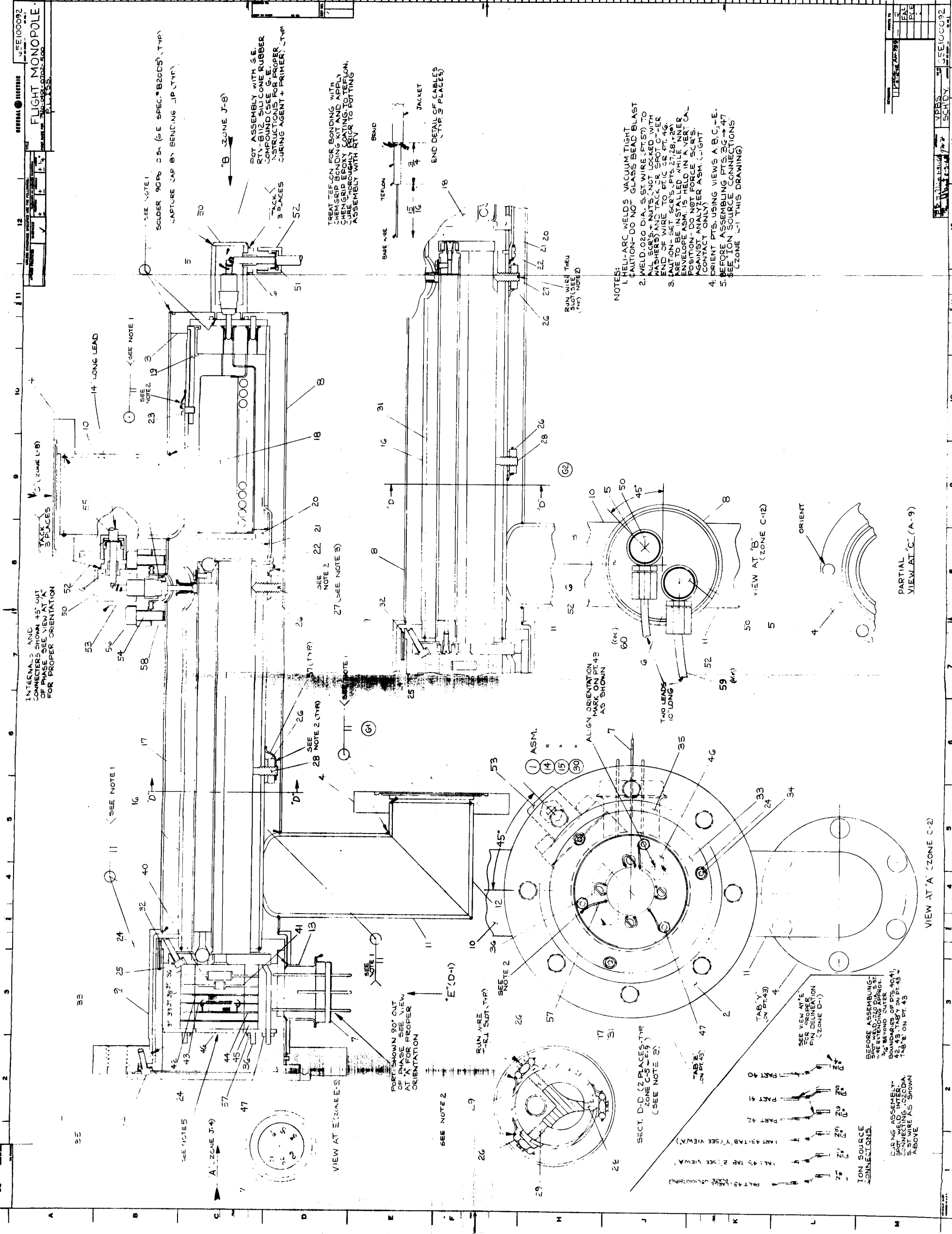


Fig. B2



- NOTES:
1. HELI-ARC WELDS VACUUM TIGHT
 2. CAUTION-DO NOT GLASS BEAD BLAST
 3. WELD .020 DIA. ST WIRE (PT. 57) TO ALL SCRS. NUTS (NOT LOCKED WITH WASHERS) AND TACK OR SPOT WELDER END OF WIRE TO PT. 10 SC. PT. 4G.
 4. POSITION BEHIND SOLDER WIRE ENVELOPE ASM. HELD IN A VERTICAL POSITION-DO NOT FORCE SCRS. AGAINST ANALYZER ASM. (LIGHT CONTACT ONLY)
 5. ORIENT PITS USING VIEWS A, B, C, E.
 6. BEFORE ASSEMBLING PITS 3G-47 SEE ION SOURCE CONNECTIONS (ZONE L-1 THIS DRAWING)

ION SOURCE CONNECTIONS

BEFORE ASSEMBLING-
SCRS. 3G-47
WIRE EXTENDING FROM
3G-47 BEYOND OUTER
BOUNDARIES OF PITS 40-41
WIRE EXTENDING FROM
TACK 43 ON PT. 43

DURING ASSEMBLY-
SCRS. 3G-47
WIRE EXTENDING FROM
TACK 43 ON PT. 43
WIRE AS SHOWN
ABOVE

PARTIAL
VIEW AT 'C' (A-9)

VIEW AT 'A' (ZONE C-2)

VIEW AT 'B' (ZONE C-12)

VIEW AT 'D' (ZONE C-1)

VIEW AT 'E' (ZONE C-3)

VIEW AT 'F' (ZONE C-4)

VIEW AT 'G' (ZONE C-5)

VIEW AT 'H' (ZONE C-6)

VIEW AT 'J' (ZONE C-7)

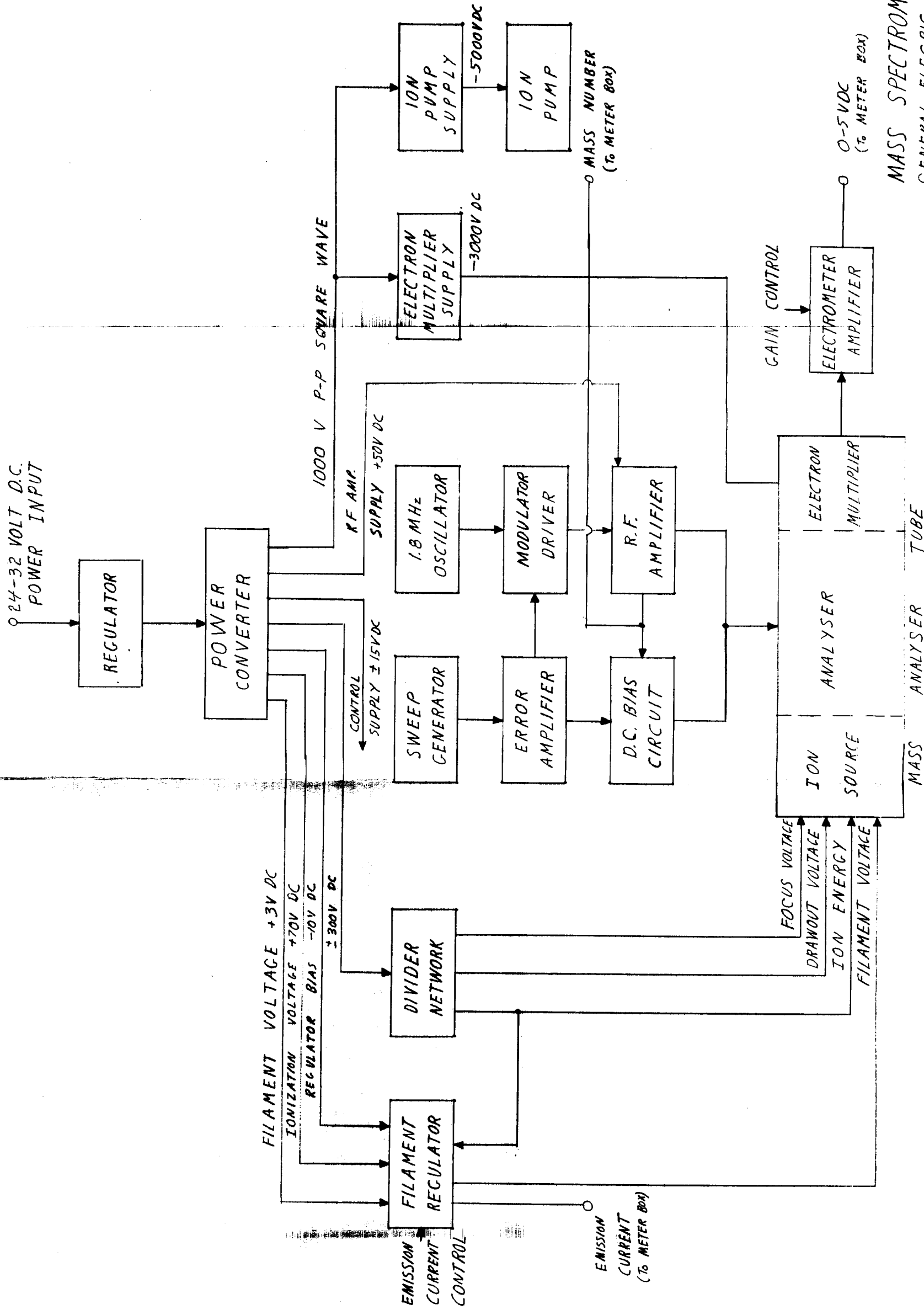
VIEW AT 'K' (ZONE C-8)

VIEW AT 'L' (ZONE C-9)

VIEW AT 'M' (ZONE C-10)

FOLDOUT FRAME

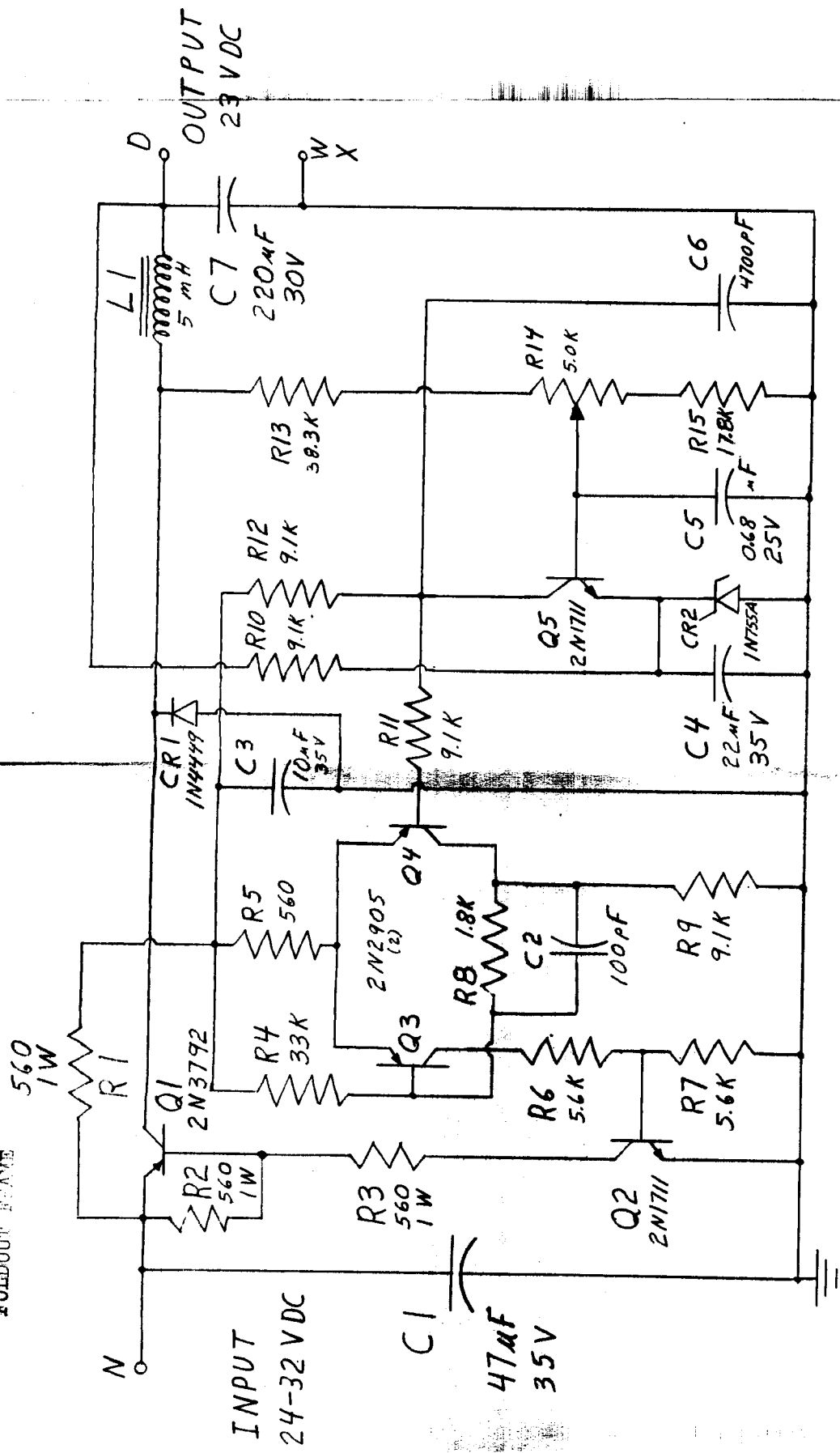
FOLDOUT FRAME



MASS SPECTROMETER
GENERAL ELECTRIC CO
APOLLO SYSTEMS DEPT
DAYTONA BEACH FLORIDA
SK-56137-4-382-101
REV 1

FOLDOUT FRAME

FOLDOUT FRAME

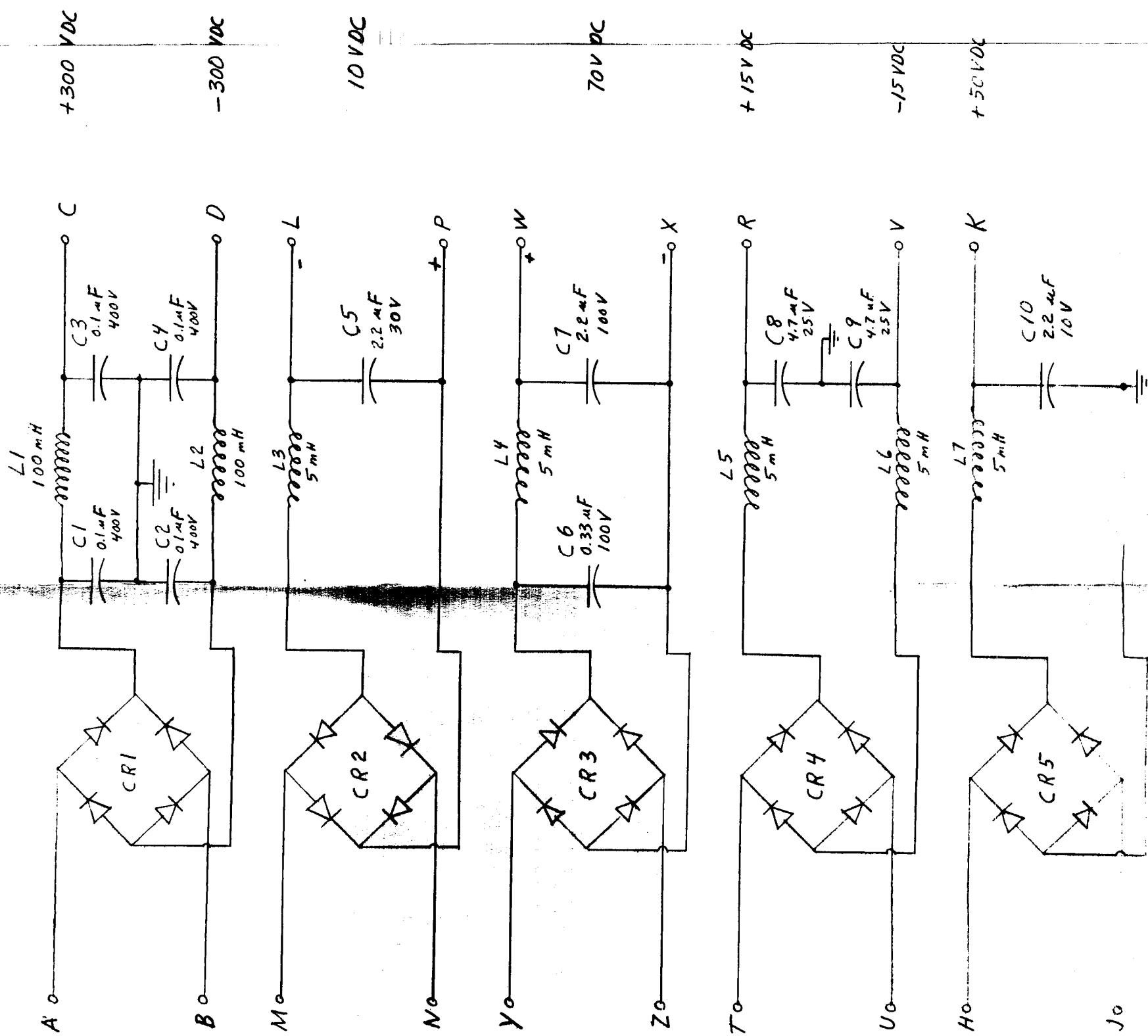


BOARD MS-1 REGULATOR

General Electric Co.
Apollo Systems Dept.
Daytona Beach, Florida
Shannon Little March 30, 1968
SK-56137-4-382-102
Rev. 1

FOLDOUT FRAME

FOLDOUT



BOARD MS-2
POWER CONVERTER II

GENERAL ELECTRIC CO.
APOLLO SYSTEMS DEPT.
Daytona Beach, Florida
Shannon Little April 8, 1968
SK-56137-4-382-103

REV. I

FOLDOUT F-AM-3



POWER CONVERTER I

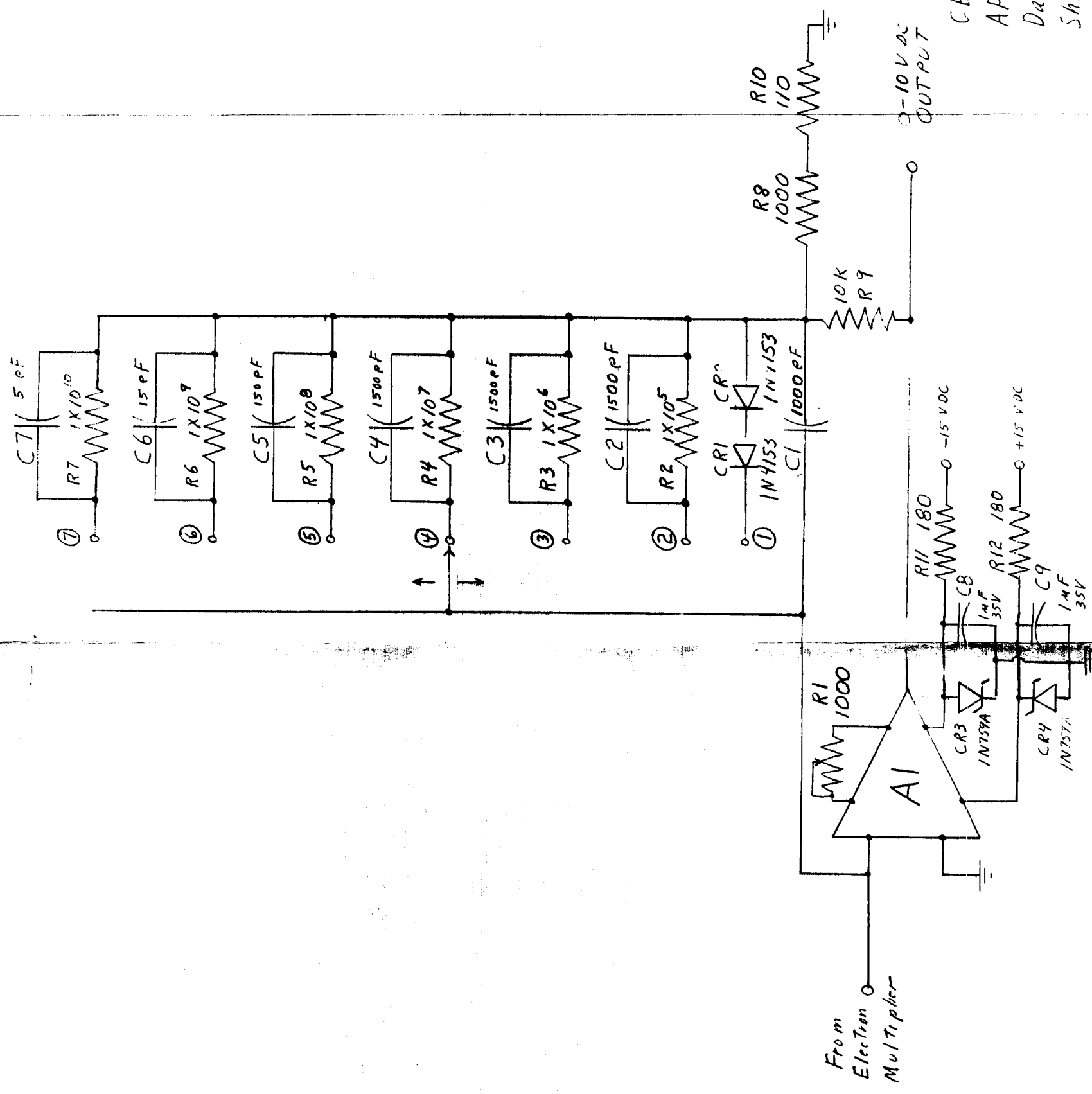
APOLLO SYSTEMS DEPT.

Shannon Little April 8, 1968

Rev. 1

FOLDOUT

FOLDOUT

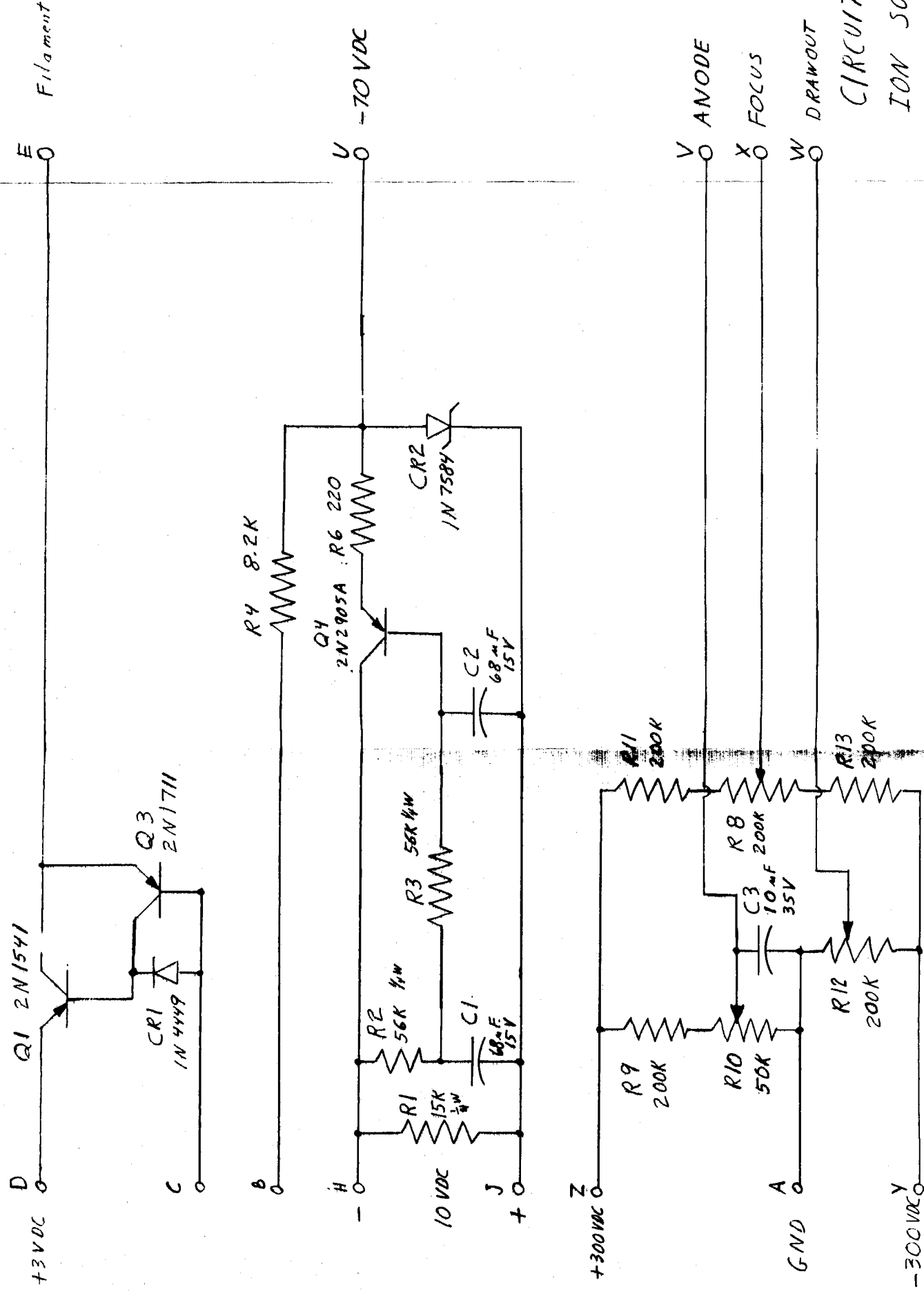


ELECTROMETER AMP.

GENERAL ELECTRIC CO.
APOLLO SYSTEMS DEPT.
Daytona Beach, Florida
Shannon Little April 8, 1968
SK-56137 4-392-105
Rev. 1

FOLDOUT FRAME

FOLDOUT - 4.1E

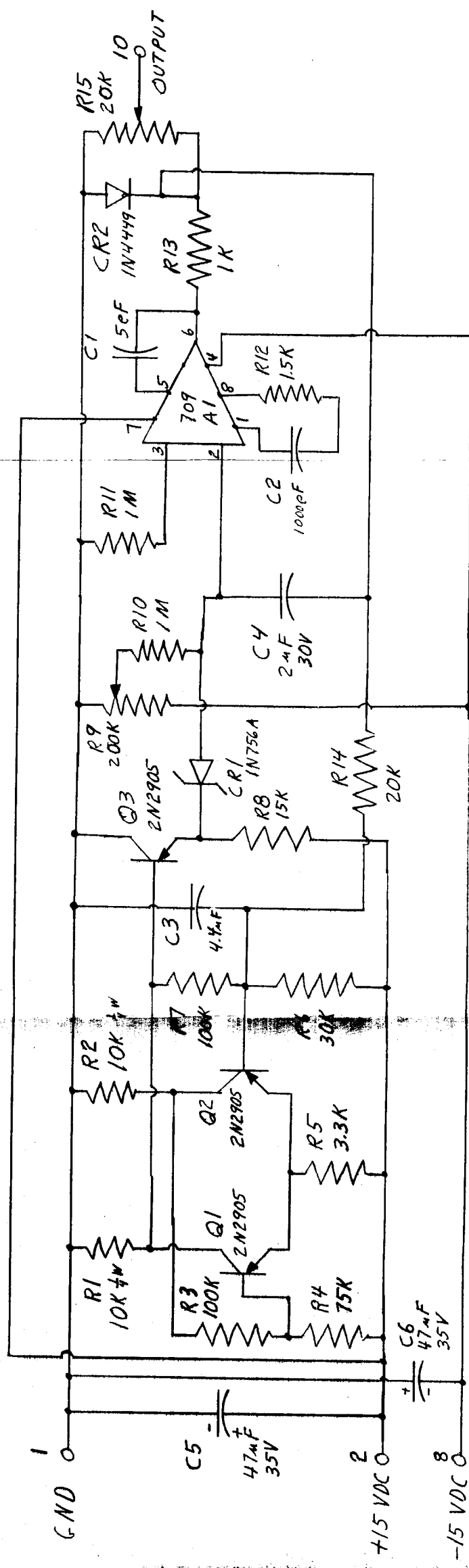


CIRCUIT BOARD MS-5
ION SOURCE CONTROL

GENERAL ELECTRIC CO.
APOLLO SYSTEMS DEPT.
Daytona Beach, Florida
Shannon Little April 8, 1968
SK 56137 4-382-106
RF 1 DEPT. 6.2

FOLDED FRAME

FOLDOUT PAGE

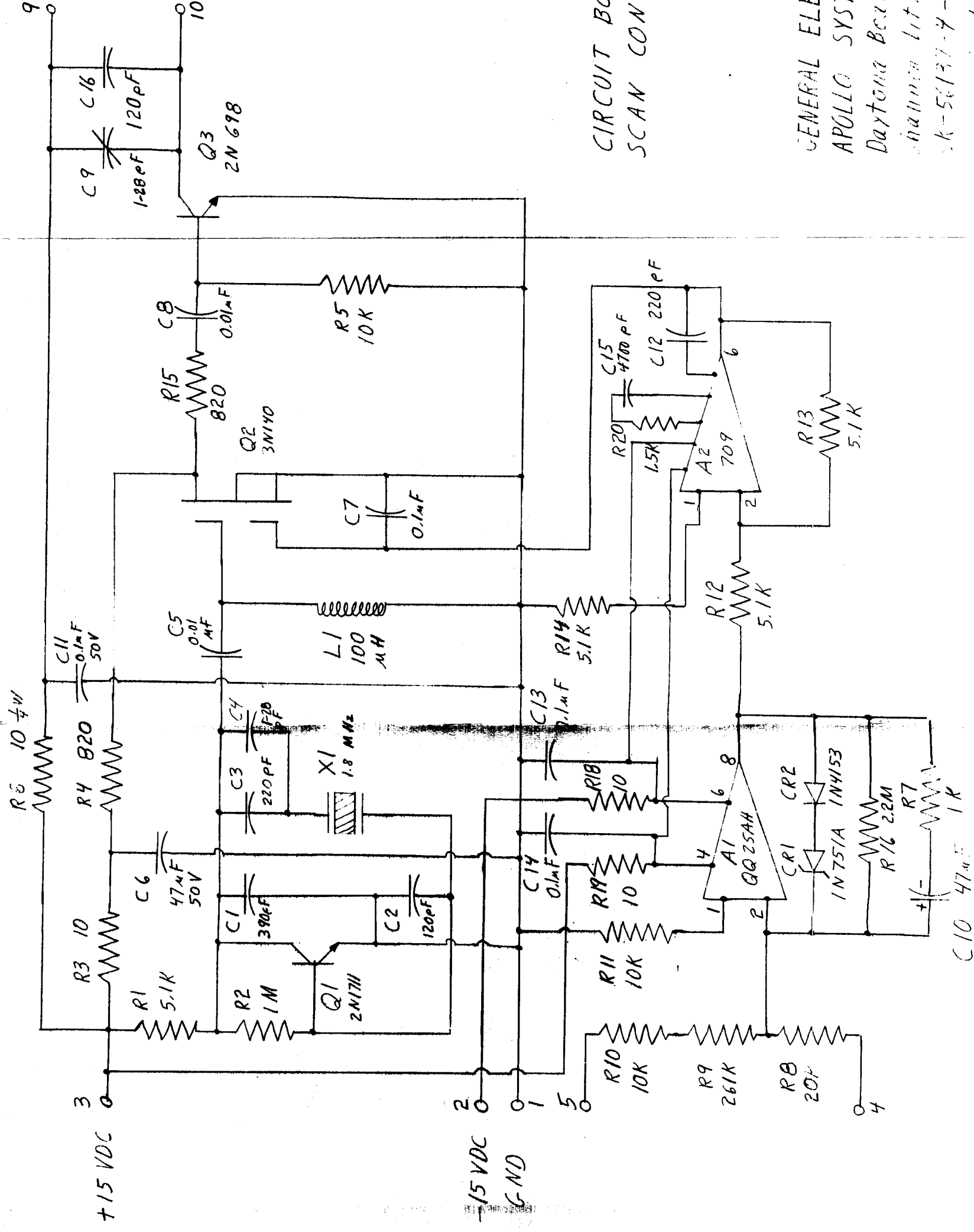


CIRCUIT BOARD MS-6
SWEEP GENERATOR

GENERAL ELECTRIC CO.
APOLLO SYSTEMS DEPT.
Dayton Beach, Florida
Shannon Little April 8, 1968
SK-56137-4-392-107
Rev 1

FOLDOUT = FOLDOUT

FOLDOUT FRAME

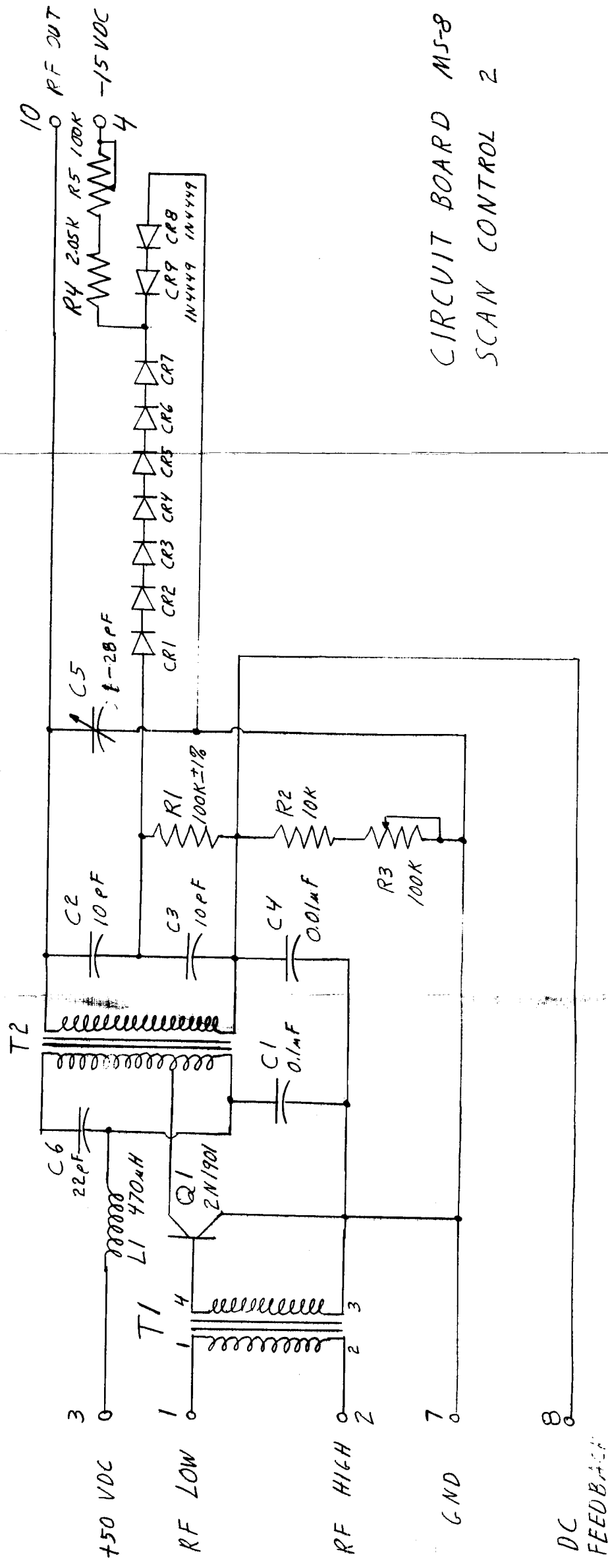


CIRCUIT BOARD MS-7
SCAN CONTROL 1

GENERAL ELECTRIC CO.
APOLLO SYSTEMS DEPT.
Daytona Beach, Florida
Shannon Little Apr 18, 1968
sk-56137-4-392-1/5

FOLDOUT FRAME

FOLDOUT FRAME



CIRCUIT BOARD MS-8
SCAN CONTROL 2

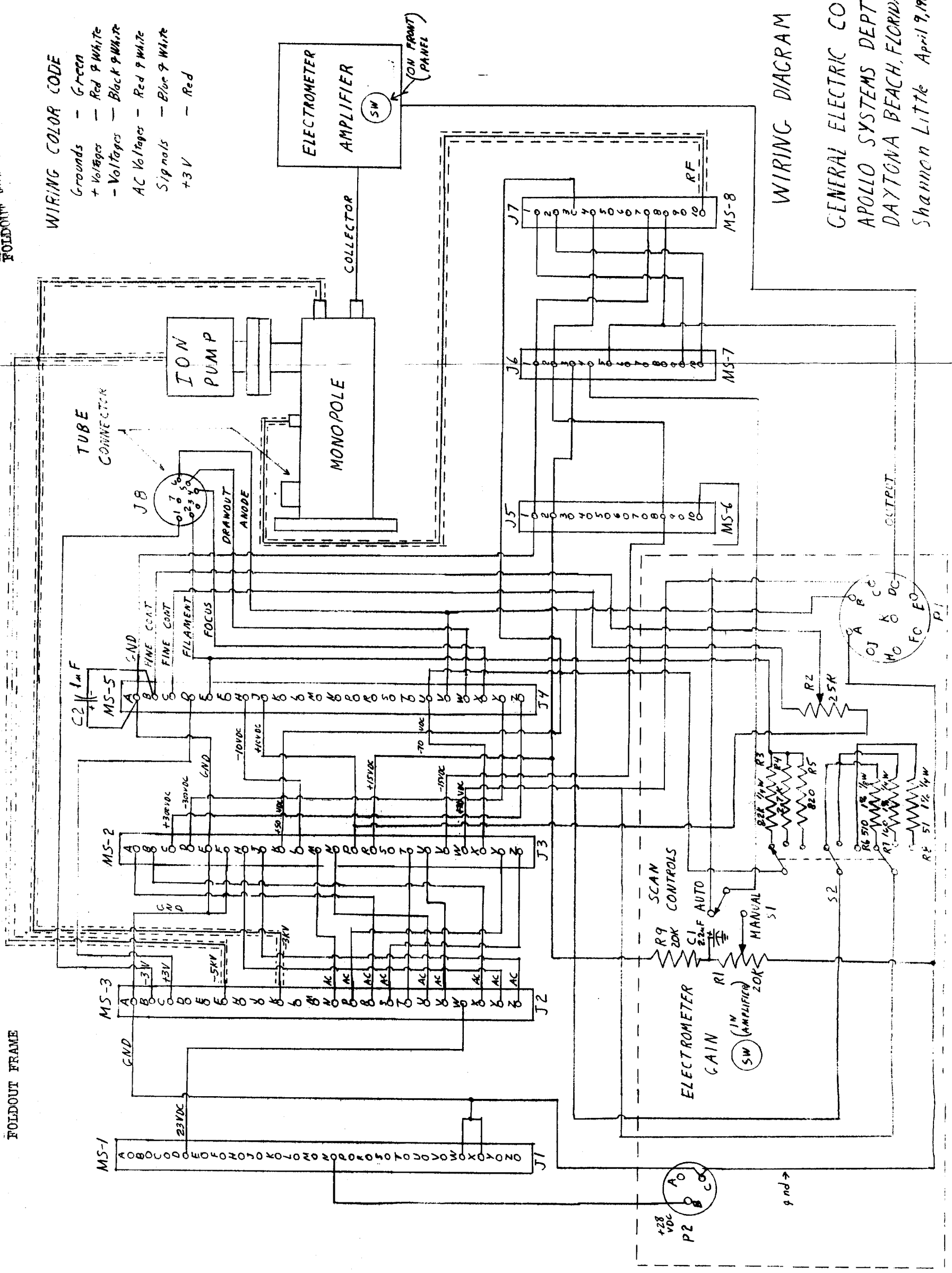
GENERAL ELECTRIC CO.
APOLLO SYSTEMS DEPT.
Daytona Beach, Florida
Shannon Little April 8, 1968
SK-56137-4-352-1C9
Rev. 2

FOLODOIT

FOLODOIT FRAME

WIRING COLOR CODE

- Grounds - Green
- + Voltages - Red & White
- Voltages - Black & White
- AC Voltages - Red & White
- Signals - Blue & White
- +3 V - Red



WIRING DIAGRAM

GENERAL ELECTRIC CO
APOLLO SYSTEMS DEPT
DAYTONA BEACH, FLORIDA
Shannon Little April 9, 1968

SK-56137-4-352-110

REV 1